

low, when compared to existing switches.

TITLE**PIEZOELECTRIC SWITCH FOR TUNABLE ELECTRONIC COMPONENTS****CLAIM OF BENEFIT OF PROVISIONAL APPLICATION**

- 5 This application claims the benefit of United States provisional application Serial No. 60/420,175 filed on October 21, 2002, which is incorporated herein by reference in its entirety.

CROSS-REFERENCE TO RELATED APPLICATIONS

- 10 The present document is related to the copending and commonly assigned patent application documents entitled "Variable Capacitance Membrane Actuator for Wide Band Tuning Microstrip Resonators and Filters," U.S. Serial No. 10/421,302, and "Piezoelectric Actuator for Tunable Electronic Components," U.S. Serial No. 10/421,303. The contents of these related applications are hereby incorporated by reference herein.

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FIELD OF THE INVENTION

The present invention relates to micro-electromechanical systems (MEMS) and, in particular, to a piezoelectric switch for tunable electronic components which can achieve substantial deflections, while keeping the overall switch dimensions small.

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BACKGROUND OF THE INVENTION

MEMS switches have a wide variety of uses. They can, for example, conduct RF current in applications involving the use of antenna phase shifters, in the tuning of reconfigurable antenna elements and in the fabrication of tunable filters.

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- MEMS switches provide several advantages over conventional switches which use transistors. These advantages include lower insertion loss, improved electrical isolation over a broad frequency range, and lower power consumption. Also, as this type of switch is fabricated using existing integrated circuit (IC) processing technologies, production costs are relatively low. Thus, MEMS switches manufactured using micromachining techniques have advantages over conventional transistor-based

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switches because the MEMS switches function like macroscopic mechanical switches, but without the associated bulk and relatively high cost.

5 The energy that must be moved through the switch control in order to activate the MEMS switch, and thus the energy dissipated by the MEMS switch, is a function of the actuation voltage. Therefore, in order to minimize the energy dissipated by the MEMS switch, it is desirable to minimize the actuation voltage of the switch.

10 Current MEMS switches operate through adoption of electrostatic techniques. In order to have low actuation voltages (about 50 V), existing electrostatic actuation switches need to have relatively large (about 300 to 500 microns) lateral dimensions. This results in an increased response time. A substantial reduction in the size of these switches is not possible as that significantly increases the actuation voltages. Therefore, electrostatic actuation MEMS switches cannot be further miniaturized as required for further applications. The large dimensions also reduce the restoring force for switch release, thus contributing to a 'stiction' problem that essentially renders the switch useless. In particular, the contacting pads tend to adhere to each other after a prolonged use.

20 Piezoelectric structures can be used to realize tunable capacitors, as disclosed in "Micromachined RF Mems tunable capacitors using piezoelectric actuators", Jae Y. Park, Young J. Yee, Hyo J. Nam, and Jong U. Bu, IEEE 2001.

In view of the foregoing, there is a need for a micro-electromechanical switch having a low actuation voltage and a fast response time.

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SUMMARY OF THE INVENTION

The present invention provides a novel layered (unimorph, bimorph or multimorph) piezoelectric switch that requires a very low actuation voltage (about 10 V), while keeping the overall lateral dimensions small (about 60 μm).

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This is made possible by applying opposing (or crossed) actuation voltages across the length of the switch, causing a 'S' shaped switch deformation. The switch has a fast

response time (about 2 microseconds) and avoids the problems associated with conventional electrostatic switches.

5 Additionally, this is made possible by a piezoelectric-electrostatic switch that uses a novel approach of combining the piezoelectric and electrostatic effects without using any extra electrodes on the active layer, allowing voltages significantly lower as compared to electrostatic switches of similar dimensions.

10 According to a first aspect of the present invention, a piezoelectric actuator is provided, comprising: an upper piezoelectric layer; a lower piezoelectric layer; a first electrode placed under the lower piezoelectric layer; a second electrode and a third electrode placed between the upper layer and the lower layer; and a fourth electrode placed above the upper piezoelectric layer.

15 According to a second aspect of the present invention, a deformable micro electromechanical structure is provided, comprising: a piezoelectric layer having a first side and a second side; a first electrode connected with the first side of the piezoelectric layer; a second electrode connected with the second side of the piezoelectric layer and with a first voltage having a first polarity; and a third electrode connected with the
20 second side of the piezoelectric layer and with a second voltage having a second polarity opposite the first polarity, whereby said structure undergoes a substantially S-shaped deformation upon application of said voltage.

25 According to a third aspect of the present invention, a method of fabricating a micro electromechanical switch on a substrate is provided; the method comprising the steps of: providing a substrate; depositing a first metal layer on the substrate; depositing a sacrificial layer on the substrate and on the first metal layer; depositing a second metal layer on the sacrificial layer; depositing a support layer on the sacrificial layer and the second metal layer; depositing a third metal layer on the support layer; depositing a
30 first piezoelectric layer on the third metal layer; depositing a fourth metal layer on the first piezoelectric layer; patterning the fourth metal layer to form two separate metal layers on the first piezoelectric layer; and removing the sacrificial layer.

According to a fourth aspect of the present invention, a method of fabricating a micro electromechanical switch on a substrate is provided, comprising the steps of: providing a substrate; depositing a first metal layer on the substrate; depositing a sacrificial layer on the substrate and on the first metal layer; depositing a support layer on the sacrificial layer; depositing a second metal layer on the support layer and patterning the second metal layer to form a first contact pad; depositing a separation layer on the support layer and the first contact pad; depositing a third metal layer on the separation layer; depositing a first piezoelectric layer on the third metal layer; depositing a fourth metal layer on the first piezoelectric layer; and removing the sacrificial layer.

According to a fifth aspect of the present invention, a micro electromechanical switch formed on a substrate is provided, comprising: an upper piezoelectric layer; a lower piezoelectric layer; a first electrode placed under the lower piezoelectric layer; a second electrode placed between the upper piezoelectric layer and the lower piezoelectric layer; and a third electrode placed on the upper piezoelectric layer.

According to a sixth aspect of the present invention, a micro electromechanical switch is provided, formed on a substrate and operating under a combined piezoelectric and electrostatic effect, the switch comprising: a first piezoelectric layer; a second piezoelectric layer; a first electrode placed under the second piezoelectric layer; a second electrode placed between the first piezoelectric layer and the second piezoelectric layer; a third electrode placed on the first piezoelectric layer; and a fourth electrode placed on the substrate.

According to a seventh aspect, a method of fabricating a micro electromechanical switch on a substrate is provided, comprising the steps of: providing a substrate; depositing a first metal layer on the substrate; patterning the first metal layer to form two separate metal layers on the substrate; depositing a sacrificial layer on the substrate and on the two separate metal layers; depositing a second metal layer on the sacrificial layer; depositing a support layer on the second metal layer and the sacrificial layer; depositing a third metal layer on the support layer; depositing a first piezoelectric layer on the

third metal layer; depositing a fourth metal layer on the first piezoelectric layer; and removing the sacrificial layer.

5 According to an eighth aspect, a method of fabricating a micro electromechanical switch on a substrate is provided, comprising the steps of: providing a substrate; depositing a first metal layer on the substrate; patterning the first metal layer to form two separate metal layers on the substrate; depositing a sacrificial layer on the substrate and on the two separate metal layers; depositing a support layer on the sacrificial layer; depositing a second metal layer on the support layer and patterning the second metal layer to
10 form a first contact pad; depositing a separation layer on the support layer and the first contact pad; depositing a third metal layer on the separation layer; depositing a first piezoelectric layer on the third metal layer; depositing a fourth metal layer on the first piezoelectric layer; and removing the sacrificial layer.

15 According to a ninth aspect, a micro electromechanical switch is provided, formed on a substrate and operating under a combined piezoelectric and electrostatic effect, the switch comprising: a first piezoelectric layer; a second piezoelectric layer; a first electrode placed under the second piezoelectric layer; a second electrode and a third electrode placed between the first piezoelectric layer and the second piezoelectric layer;
20 a fourth electrode placed on the first piezoelectric layer; and a fifth electrode placed on the substrate.

Compared to existing switch designs, the invention possesses substantially reduced lateral dimensions, while further lowering actuation voltages to about 10 V. This small
25 size enables the invention to achieve much faster (about 1 microsecond) response times. In addition, a large restoring force can be generated to release the switch, thereby alleviating the severe problem of stiction associated with most switch designs.

30 BRIEF DESCRIPTION OF THE DRAWINGS

The features and advantages of the present invention will become better understood with regard to the following description, appended claims, and accompanying drawings

where:

Figures 1A-1C show schematic views of a two-layered piezoelectric actuator with parallel polarization directions, to be used in accordance with the present invention;

5 Figures 2A-2C show views of a MEMS switch according to a first embodiment of the present invention, wherein Figure 2A shows the switch in an open position and Figure 2C shows the switch in a closed position;

Figures 3A-3B show views of a MEMS switch according to a second embodiment of the present invention, wherein Figure 3A shows the switch in an open position and Figure 3B shows the switch in a closed position;

10 Figures 4A-4F and 5A-5E show process steps in fabricating the switch of Figures 2A-2C; Figures 6A-6F show an alternate embodiment of the fabricating steps shown in Figures 4C-4F, respectively;

Figures 7A-7B show views of a MEMS switch according to a third embodiment of the present invention, wherein Figure 7A shows the switch in an open position and Figure 7B shows the switch in a closed position;

Figures 8A-8C show views of a MEMS switch according to a fourth embodiment of the present invention, wherein Figure 8A shows the switch in an open position and Figure 8C shows the switch in a closed position;

20 Figures 9A-9F and 10A-10E show process steps in fabricating the switch of Figures 8A-8C;

Figures 11A-11F show an alternate embodiment of the fabricating steps shown in Figures 9C-9F, respectively; and

25 Figures 12A-12B show views of a MEMS switch according to a fifth embodiment of the present invention, wherein Figure 12A shows the switch in an open position and Figure 12B shows the switch in a closed position.

DETAILED DESCRIPTION OF THE INVENTION

30 Figures 1A to 1C show schematic views of a two-layered piezoelectric actuator with parallel polarization directions to be used in accordance with the present invention. The polarization directions are shown by the small arrows depicted within each layer. The actuator shown in Figures 1A-1C comprises an upper layer 1 and a lower layer 2. The layers 1, 2 are made, for example, of lead zirconate titanate (PZT) or lead lanthanum

zirconate titanate (PLZT).

Electrodes 3, 4, and 5, shown in Figs. 1A-1C, are alternated with layers 1 and 2. Layers 1 and 2 deflect on applying voltages between the electrodes 3, 4 and 5. On choosing the proper polarities for the voltage, a tensile force T1 or thrusting force T2 can be generated in the plane of the layers 1, 2. The forces T1, T2 will create a deflection in the middle section of the layers 1, 2. For a given piezoelectric material such as PZT or PLZT, the amount of deflection and force depends on the dimension of the layers, which can be adjusted to meet the requirements of the particular application. When no voltage is applied, the actuator does not cause the piezoelectric layer to be deflected, as shown in Figure 1A. When voltage having a first polarity is applied, for example a positive polarity, the actuator causes the piezoelectric layer to be deflected in a first direction, for example upwards, as shown in Figure 1B. When voltage having a second polarity, opposite to the first polarity (i.e. having a sign which is different from the sign of the first polarity), is applied, for example a negative polarity, the actuator causes the piezoelectric layer to be deflected in a second direction, for example downwards, as shown in Figure 1C.

Figs. 2A-2C show a switch according to a first embodiment of the present invention. The switch, generally designated 100, is fabricated on a substrate 117 using generally known microfabrication techniques, such as masking, etching, deposition, and lift-off. In a preferred embodiment, the switch 100 is directly formed on the substrate 117. Alternatively, the switch 100 may be discreetly formed and then bonded to the substrate 117.

The switch 100 comprises an upper piezoelectric layer 110, a lower piezoelectric layer 111, a first electrode 112 placed under the lower layer 111, a second electrode 113 placed between the upper layer 110 and the lower layer 111, a third electrode 114 placed between the upper layer 110 and the lower layer 111, a fourth electrode 115 placed above the upper layer 110, and a Si_3N_4 layer 116 placed under the electrode 112. In the preferred embodiment, shown in the figure, the electrode 112 extends along the whole

length of the piezoelectric layer 111, in order to avoid contact between the piezoelectric layer 111 and the Si_3N_4 layer 116, which contact is sometimes undesired. A spacer 118 acting as a cantilever anchor separates the switch 100 from the substrate 117. Additionally, a first contact pad 119 is provided under the Si_3N_4 layer 116, and a second contact pad 120 is provided above the substrate 117. The first contact pad 119 operates as an electrical contact of the switch 100. Figure 2A shows the switch in an 'OFF' position (contact pads 119, 120 separated). The contact pad 119, typically comprising a metal that does not oxidize easily, such as gold, platinum, titanium-platinum or titanium-gold, is positioned so as to face the second contact pad 120 on the substrate 117. Also the contact pad 120 typically comprises a metal that does not oxidize easily, such as gold, or platinum.

The switch 100 has a bilaminar cantilever (or bimorph) structure, that is, the structure comprises two active layers, layer 110 and layer 111. Due to the structure of the switch and to the mechanical properties of the piezoelectric material used for layers 110 and 111, the bimorph structure is piezoelectrically actuatable and has the advantage of exhibiting a very high ratio of displacement to actuation voltage. As a consequence, a relatively large displacement (approximately 1-2 microns) can be produced in the bimorph cantilever in response to a relatively low switching voltage (approximately 10 V).

The thickness of the layers 110, 120 and electrodes 112, 113, 114 and 115 and the height of the cantilever anchor 118 can be tightly controlled using known fabrication methods. The distance between the contact pads 119, 120 is, for example, about 1 micron. The length of the piezoelectric layers is, for example, about 70 microns. The piezoelectric layers 110, 111 are made, for example, of a PZT layer or a PLZT layer.

Figure 2B shows in greater detail the preferred shape of the second electrode 113 and third electrode 114 placed above the lower layer 111 and comprising respective contacts 113' and 114' to a voltage source, not shown in the Figure. For example, the second electrode 113 can be connected to a negative voltage (e.g. -10 V) and the third electrode

114 can be connected to a positive voltage (e.g. +10 V).

The operation of the first embodiment will now be discussed with reference to Fig. 2C. In operation, the switch 100 is normally in an open, or "OFF," position as shown in Fig. 2A. The switch 100 is actuated to the closed, or "ON," position by application of a voltage between the four electrodes 112, 113, 114, and 115. More precisely, a positive voltage +V is applied to the third electrode 114, a negative voltage -V is applied to the second electrode 113, and the first electrode 112 and fourth electrode 115 are kept at ground voltage. When the voltage is applied, the left portion of the bimorph structure of Fig. 2C deflects as shown in Fig. 1C, and the right portion of the bimorph structure of Fig. 2C deflects as shown in Fig. 1B.

As a consequence, an 'S' shaped deformation or deflection is obtained, as shown in Fig. 2C. The 'S' shaped deformation is obtained by virtue of the 'crossed' actuation voltages applied to the second and third electrodes 113, 114, where the second electrode 113 is provided with a voltage having a first polarity (for example a negative voltage -V) and the third electrode 114 is provided with a voltage having a second polarity different from the first polarity (for example a positive voltage +V). By means of the deflection, the metal pad 119 is moved downwards and is brought into contact with the pad 120, thus actuating the switch to the "ON" position.

Also structures having a single piezoelectric or active layer are possible. An example of such structures is shown in Figures 3A and 3B. Figures 3A and 3B are similar to Figures 2A and 2C, respectively, the main difference being that the top piezoelectric layer 110 and the fourth electrode 115 are not provided. Also in this additional embodiment, an 'S' shaped deformation is obtained, due to the presence of the electrodes 213, 214 and to the opposite voltages -V, +V, shown in Figure 3B, applied thereto.

One possible method of fabricating the switch 100 will now be described in Figures 4A-4F and Figures 5A-5E. The switch 100 may be manufactured using generally known microfabrication techniques, such as masking, etching, deposition and lift-off. The switch 100 may be fabricated using, for example, a foundry-based polysilicon surface-

micromachining process, or a metal/insulator surface-micromachining process. The substrate 117 for one preferred embodiment may be a GaAs wafer, although other materials such as GaN, InP, ceramics, quartz or silicon may be used. Note that the switch 100 may be fabricated by processes other than that depicted in Figs. 4 and 5.

5 Further, while Figs. 4 and 5 depict multiple separate fabrication steps, alternative fabrication processes may allow several separate steps to be combined into fewer steps. Finally, alternative fabrication processes may use a different sequence of steps.

10 Figure 4A shows a first step of the process, where the substrate 117 is provided and a first metal layer is deposited on the substrate 117. The first metal layer is patterned to form the bottom contact pad 120 using, for example, electron beam evaporation and liftoff. The metal layer is, for example, a 0.2 μm thick Ti/Pt layer.

15 Figure 4B shows a second step of the process, where a sacrificial layer 130 is deposited on the substrate 117 and on the metal layer forming the contact pad 120. A sacrificial layer is a layer which is first deposited in a step of a process and then removed in a further step of the process. The thickness of the layer 130 determines the air gap (i.e. the distance between the contact pads 119 and 120) for the switch. The sacrificial layer 130 is, for example, a 1 μm thick layer made of silicon dioxide (SiO_2) which may be deposited
20 using PECVD (Plasma Enhanced Chemical Vapor Deposition).

Figure 4C shows a third step of the process, where a second metal layer forming the top contact pad 119 of the switch 100 is deposited on the sacrificial layer 130. The second metal layer is patterned to form the top contact pad 119 using, for example, electron
25 beam evaporation and liftoff. The second metal layer is, for example, a 0.2 μm thick Ti/Pt layer.

Figure 4D shows a fourth step of the process, where the sacrificial layer 130 is etched (for example dry or wet etching) after deposition and patterning of a photoresist layer,
30 not shown in the figure. The etching step creates a hole 150 in the structure.

Figure 4E shows a fifth step of the process, where a layer 131 is deposited above the sacrificial layer 130, the top contact pad 119 and the hole 150. The layer 131 is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD. The layer 131 will be patterned to form the layer 116 shown in Fig. 2A. The use of the layer 131 is preferred, because it provides support and mechanical strength to the final released structure. The thickness of the layer 131 may be adjusted to compensate for any stress related bending.

The layer 131 can be patterned at the present stage or later, depending on the etch method used for the piezoelectric layer 111 in Figure 5A below. Should the piezoelectric layer 111 of Figure 5A be etched through a dry etch process, the layer 131 can be patterned at the present stage. Should the piezoelectric layer 111 of Figure 5A be etched through a wet etch process, the layer 131 is preferably patterned at a later stage, because it serves to protect the underlying sacrificial layer 130 from the etching chemicals, some of which may attack the sacrificial layer 130.

Figure 4F shows a sixth step of the process, where a third metal layer, forming the first electrode 112, is deposited above the layer 131. The layer forming the first electrode 112 is, for example, a 0.2 μm thick Ti/Pt layer deposited using liftoff technique.

Figure 5A shows a seventh step of the process, where a first piezoelectric layer, forming the lower piezoelectric layer 111, is deposited. The layer 111 is, for example, a 0.5 μm thick PZT or PLZT layer deposited using, for example, sol-gel deposition technique. Such technique is known to the person skilled in the art and will not be described in detail. The process of depositing the layer 111 preferably involves an annealing step at about 500-700 $^{\circ}\text{C}$. The layer 111 can be patterned using a variety of dry or wet etch techniques.

Figure 5B shows an eighth step of the process, where a fourth metal layer is deposited above the layer 111 and patterned to form the second electrode 113 and the fourth electrode 114. The electrodes 113 and 114 are formed, for example, by a 0.2 μm thick

Ti/Pt layer deposited using electron beam evaporation and liftoff.

Figure 5C shows a ninth step of the process, where a second piezoelectric layer forming the upper piezoelectric layer 110 is deposited. The layer 110 is, for example, a 0.5 μm thick PZT or PLZT layer deposited using, for example, a sol-gel deposition technique.

Figure 5D shows a tenth step of the process, where a fifth metal layer forming the fourth electrode 115 is deposited above the upper piezoelectric layer 110. The fifth metal layer is, for example, a 0.2 μm thick Ti/Pt layer deposited using electron beam evaporation and liftoff.

Figure 5E shows an eleventh step of the process, where the sacrificial layer 130 is removed by using chemical release methods known in the art, for example by means of hydrofluoric acid (HF).

With reference to the single-layered structure shown in Figures 3A and 3B, such structure can be obtained through the steps shown in Figures 4A-4F combined with the steps shown in Figures 5A, 5B and 5E.

It will also be appreciated that the spacer 118 shown in Figures 2A and 2C is formed, in the preferred embodiment, by the left portion of the layers 111 and 131.

Figures 6A-6F show an alternative embodiment of the steps shown in Figures 4C-4F, respectively.

Figure 6A shows an alternate third step of the process, where the sacrificial layer 130 is etched (for example dry or wet etching) after deposition and patterning of a photoresist layer, not shown in the figure. The etching step creates the hole 150 in the structure.

Figure 6B shows an alternate fourth step of the process, following the alternate third step of Figure 6A, where a layer 331 is deposited above the sacrificial layer 130. The

layer 331 is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD. The layer 331 is patterned to form portions 331a and 331b. The region between portions 331a and 331b is indicated 160.

- 5 Figure 6C shows an alternate fifth step of the process, following the alternate fourth step of Figure 6B, where the region 160 is dry or wet etched to form a trench 170 having a preferred depth of about 0.25 μm to about 0.5 μm .

- 10 Figure 6D shows an alternate sixth step of the process, following the alternate fifth step of Figure 6C, where a metal layer forming a top contact pad 319 is deposited and patterned on the sacrificial layer 130, in and above the trench 170.

- 15 Figure 6E shows an alternate seventh step of the process, following the alternate sixth step of Figure 6D, where a non-metal separation layer 331c is deposited above the layers 331a, 331b and the top contact pad 319. The layer 331c is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD.

- 20 Figure 6F shows an alternate eighth step of the process, following the alternate seventh step of Figure 6E, where a metal layer 112 is deposited above the layer 331c.

The alternate embodiment shown in Figures 6A-6F ensures that the top contact pad 319 is held more securely between the Si_3N_4 and PZT layers and that a better contact with the bottom pad 120 is obtained.

- 25 Figures 7A-7B show a switch according to a third embodiment of the present invention, where only three electrodes are used, and cross voltages are applied to the upper and lower electrodes.

- 30 Figure 7A shows a switch 300 comprising an upper piezoelectric layer 310, a lower piezoelectric layer 311, a first or lower electrode 312 placed under the lower layer 311, a second or middle electrode 313 placed between the upper layer 310 and the lower layer

311, and a third or upper electrode 315 placed above the upper layer 310. A Si_3N_4 layer 316 is connected to the electrode 312 and placed under the electrode 312. The switch 300 is placed above a substrate 317 and spaced from the substrate 317 by means of a spacer 318. Additionally, a first contact pad 319 is provided under the second electrode 312 and
5 a second contact pad 320 is provided above the substrate 317.

Also in the third embodiment, an 'S' shaped deformation or deflection is obtained upon application of a voltage, as shown in Fig. 7B. The 'S' shaped deformation is obtained by virtue of the 'crossed' actuation voltages applied to the lower and upper electrodes 312,
10 315, where the lower electrode 312 is provided with a voltage having a first polarity (for example a negative voltage -V) and the upper electrode 315 is provided with a voltage having a second polarity different from the first polarity (for example a positive voltage +V). By means of the deflection, the metal pad 319 is moved downwards and is brought into contact with the pad 320, thus actuating the switch to the "ON" position.

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As already pointed out above, the third embodiment allows only three electrodes to be used instead of four. However, higher voltages than those employed in the first two embodiments are required.

20 Figures 8A-8C show a switch according to a fourth embodiment of the present invention, where switching occurs according to a combination between electrostatic effect and piezoelectric effect. In particular, combination of the electrostatic effect with the embodiment of Figures 7A and 7B is shown.

25 Figure 8A shows a switch 400 comprising an upper piezoelectric layer 410, a lower piezoelectric layer 411, a first or lower electrode 412 placed under the lower layer 411, a second or middle electrode 413 placed between the upper layer 410 and the lower layer 411, and a third or upper electrode 415 placed above the upper layer 410. A Si_3N_4 layer 416 is connected to the electrode 412 and placed under the electrode 412. The switch 400
30 is placed above a substrate 417 and spaced from the substrate 417 by means of a spacer 418. Additionally, a first contact pad 419 is provided under the second electrode 412 and

a second contact pad 420 is provided above the substrate 417. The distance between contact pads 419 and 420 is preferably 1 μm .

In this fourth embodiment, an additional electrode 421 is provided on the substrate 417.

- 5 The presence of the additional electrode 421 allows the piezoelectric effect of the switch to be combined with an electrostatic effect. The combination of the two effects has the advantage of significantly lowering the actuation voltages as compared to conventional electrostatic switches of similar dimensions.
- 10 Figure 8B shows a schematic top section of the structure of Figure 8A, taken along line 1-1 of Figure 8A. Figure 8B shows the support wall 418, the top electrode 415, and the top pad 419. Also shown in Figure 8B is an exemplary form of a contact 450 between the electrode 415 and a voltage source (not shown). As shown in Figure 8B, the electrode 415 is preferably T-shaped. In this way, a larger area of the electrode 415 is
- 15 obtained, with corresponding increase of the electrostatic actuation effect.

Dimension 'a' of Figure 8B is preferably 30 μm long. Dimensions 'b' and 'd' are preferably 10 μm long. Dimension 'c' is preferably 35 μm long. Dimension 'e' is preferably 5 μm long. Dimension f is preferably 10 μm long.

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- Also in the fourth embodiment, an 'S' shaped deformation or deflection is obtained upon application of a voltage, as shown in Fig. 8C. The 'S' shaped deformation is obtained by virtue of the 'crossed' actuation voltages applied to the lower and upper electrodes 412, 415, where the lower electrode 412 is provided with a voltage having a
- 25 first polarity (for example a negative voltage -V) and the upper electrode 415 is provided with a voltage having a second polarity different from the first polarity (for example a positive voltage +V). By means of the deflection, the metal pad 419 is moved downwards and is brought into contact with the pad 420, thus actuating the switch to the "ON" position.

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When applying opposite voltages to the lower and upper electrodes, a large initial deflection is obtained due to the piezoelectric effect. This places the electrodes for

electrostatic actuation much closer together, and a relatively small increase in the actuation voltage causes the switch to close. In particular, the piezoelectric component of the attractive force is usually linear with the dimension of the gap, while the electrostatic component of the attractive force is very small when the gap is large and
5 very high when the gap is small.

The actuation voltage of a switch having a combined piezoelectric-electrostatic effect of Figure 8C is in the range of 30-40 V. In the absence of the piezoelectric effect, i.e. for a purely electrostatic switch of similar dimensions, an actuation voltage of about 80 V
10 would be needed. Hence, the embodiment shown in Figures 8A-8C achieves a significant lowering of the actuation voltage when compared with prior art electrostatic switches. The response time is about 4 μ s.

Figure 9A-9F and 10A-10E show one possible method of fabricating the switch 400
15 described in Figures 8A-8C. The switch 400 may be manufactured using generally known microfabrication techniques, such as masking, etching, deposition and lift-off. The switch 400 may be fabricated using, for example, a foundry-based polysilicon surface-micromachining process, or a metal/insulator surface-micromachining process. The substrate 417 for one preferred embodiment may be a GaAs wafer, although other
20 materials such as Si, GaN, InP, ceramics, or quartz may be used. Note that the switch 400 may be fabricated by processes other than that depicted in Figs. 9 and 10. Further, while Figs. 9 and 10 depict multiple separate fabrication steps, alternative fabrication processes may allow several separate steps to be combined into fewer steps. Finally, alternative fabrication processes may use a different sequence of steps.

25 Figure 9A shows a first step of the process, where a substrate 417 is provided and a first metal layer is deposited on the substrate 417. The metal layer is patterned to form the bottom contact pad 420 and the bottom electrode 421 using, for example, electron beam evaporation or liftoff. The metal layer is, for example, a 0.2 μ m thick Ti/Pt layer.

30 Figure 9B shows a second step of the process, where a sacrificial layer 430 is deposited on the substrate 417 and on the bottom contact pad 420 and bottom electrode 421. The

thickness of the layer 430 determines the air gap for the switch. The layer 430 is, for example, a 1 μm thick layer made of SiO_2 , which is deposited using PECVD.

Figure 9C shows a third step of the process, where a second metal layer is deposited
5 and patterned to form the top contact pad 419.

Figure 9D shows a fourth step of the process, where the layer 430 is etched (for example dry or wet etching) after deposition and patterning of a photoresist layer, not shown in the figure. The etching step creates a hole 450 in the structure.

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Figure 9E shows a fifth step of the process, where a layer 431 is deposited. The layer 431 is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD. The layer 431 forms the layer 416 shown in Figures 8A and 8C. The presence of a layer 431 is preferred, because it provides mechanical strength to the final released
15 structure. Additionally, the layer 431 prevents a short-circuit between the electrodes 412 and 421 when the switch is closed. The thickness of the layer 431 may be adjusted to compensate for any stress related bending.

Similarly to what explained with reference to Figure 4E, the layer 431 can be patterned
20 at the present stage or later, depending on the etch method used for the piezoelectric layer 411 in Figure 10A below. Should the piezoelectric layer 411 of Figure 10A be etched through a dry etch process, the layer 431 can be patterned at the present stage. Should the piezoelectric layer 411 of Figure 10A be etched through a wet etch process, the layer 431 is preferably patterned at a later stage, because it serves to protect the
25 underlying layer 430 from the etching chemicals, some of which may attack the layer 430.

Figure 9F shows a sixth step of the process, where a second metal layer, forming the first electrode 412, is deposited above the layer 431. The second metal layer is, for
30 example, a 0.1 μm thick Ti/Pt layer deposited using liftoff technique.

Figure 10A shows a seventh step of the process, where a first piezoelectric layer forming the lower piezoelectric layer 411 is deposited. The layer 411 is, for example, a 0.5 μm thick PZT or PLZT layer deposited using a sol-gel deposition technique. The process of depositing the layer 411 involves an annealing step at about 500-700 $^{\circ}\text{C}$. The layer 411 can be patterned using a variety of dry or wet etch techniques.

Figure 10B shows an eighth step of the process, where a third metal layer, forming the second electrode 413, is deposited above the layer 411. The electrode 413 is formed, for example, by a 0.1 μm thick Ti/Pt layer deposited using liftoff technique.

Figure 10C shows a ninth step of the process, where a second piezoelectric layer forming the upper piezoelectric layer 410 is deposited. The layer 410 is, for example, a 0.5 μm thick PZT or PLZT layer deposited using, for example, a sol-gel deposition technique.

Figure 10D shows a tenth step of the process, where a fourth layer, forming the third electrode 415 is deposited above the layer 410. The deposited layer is, for example, a 0.1 μm thick Ti/Pt layer deposited using liftoff technique.

Figure 10E shows an eleventh step of the process, where the sacrificial layer 430 is removed, for example by means of hydrofluoric acid (HF).

From the process steps shown in Figures 9 and 10 it is also clear that a structure like the one depicted in Figures 7A and 7B can be obtained, the only difference being the absence of the metal element 421 in the deposition step of Figure 9B.

It will also be appreciated that the spacer 418 shown in Figures 8A-8C is formed, in the preferred embodiment, by the left portion of the layers 411 and 431.

Additionally, similarly to what shown in Figures 6A-6D, Figures 11A-11D show an alternative embodiment of the steps shown in Figures 9C-9F, respectively.

Figure 11A shows an alternate third step of the process of Figures 9 and 10, where the sacrificial layer 430 is etched (for example dry or wet etching) after deposition and patterning of a photoresist layer, not shown in the figure. The etching step creates the hole 450 in the structure.

5 Figure 11B shows an alternate fourth step of the process, following the alternate third step of Figure 11A, where a layer 531 is deposited above the sacrificial layer 430. The layer 531 is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD. The layer 531 is patterned to form portions 531a and 531b. The region
10 between portions 531a and 531b is indicated 460.

Figure 11C shows an alternate fifth step of the process, following the alternate fourth step of Figure 11B, where the region 460 is dry or wet etched to form a trench 470 having a preferred depth of about 0.25 μm to about 0.5 μm .

15 Figure 11D shows an alternate sixth step of the process, following the alternate fifth step of Figure 11C, where a metal layer forming a top contact pad 519 is deposited and patterned on the sacrificial layer 430, in and above the trench 470.

20 Figure 11E shows an alternate seventh step of the process, following the alternate sixth step of Figure 11D, where a non-metal separation layer 531c is deposited above the layers 531a, 531b and the top contact pad 519. The layer 531c is, for example, a 0.1 to 0.5 μm thick layer made of Si_3N_4 , which is deposited using PECVD.

25 Figure 11F shows an alternate eighth step of the process, following the alternate seventh step of Figure 11E, where a metal layer 412 is deposited above the layer 531c.

The alternate embodiment shown in Figures 11A-11F ensures that the top contact pad 519 is held more securely between the Si_3N_4 and PZT layers and that a better contact
30 with the bottom pad 420 is obtained.

A third embodiment of the present invention is also possible, where the electrostatic effect is combined with the 'S' shaped deflection of the embodiment of Figures 2A-2C. This embodiment is shown in Figures 12A and 12B, where similar elements to the previous embodiments have been indicated by similar numbers.

5

Although the present invention has been described with respect to specific embodiments thereof, various changes and modifications can be carried out by those skilled in the art without departing from the scope of the invention. It is intended, therefore, that the present invention encompass changes and modifications falling

10

within the scope of the appended claims.

WHAT IS CLAIMED IS:

1.

A piezoelectric actuator comprising:

- 5 an upper piezoelectric layer;
 a lower piezoelectric layer;
 a first electrode placed under the lower piezoelectric layer;
 a second electrode and a third electrode placed between the upper layer and the
lower layer; and
10 a fourth electrode placed above the upper piezoelectric layer.

2.

- The actuator of claim 1, wherein the second electrode is connected to a first voltage
having a first polarity and the third electrode is connected to a second voltage having a
15 second polarity opposite the first polarity.

3.

- The actuator of claim 1 or claim 2, wherein the actuator is a micro electromechanical
switch.
20

4.

- The switch of claim 3, wherein the second electrode is connected to a first voltage
having a first polarity and the third electrode is connected to a second voltage having
a second polarity opposite the first polarity.
25

5.

The switch of claim 4, wherein said switch is formed on a substrate.

6.

- 30 The switch of claim 4 or claim 5, further comprising a support layer connected to the
first electrode and placed under the first electrode.

7.

The switch of claim 6, wherein the support layer is a Si_3N_4 layer.

5 8.

The switch of claim 4, wherein a spacer separates the switch from the substrate.

9.

10 The switch of claim 5, further comprising a first contact pad provided under the lower piezoelectric layer and a second contact pad provided above the substrate.

10.

15 The switch of claim 9, wherein the first and second contact pad are chosen from the group consisting of gold, platinum, titanium-platinum, or titanium-gold.

11.

The switch of claim 9 or claim 10, wherein the first contact pad is positioned so as to face the second contact pad.

20 12.

The switch of any one of claims 9-11, wherein the first contact pad is separated from the second contact pad when the switch is in a first condition chosen from an ON condition and an OFF condition, and the first contact pad contacts the second contact pad when the switch is in a second condition chosen from an ON condition and an OFF condition,
25 different from the first condition.

13.

30 The switch of claim 12, wherein the switch undergoes a substantially S-shaped deformation when the first contact pad contacts the second contact pad.

14.

The switch of claim 12 or claim 13, wherein the distance between the first contact pad and the second contact pad when the switch is in said first condition is about 1 μm .

5

15.

A deformable micro electromechanical structure comprising:

a piezoelectric layer having a first side and a second side;

a first electrode connected with the first side of the piezoelectric layer;

10 a second electrode connected with the second side of the piezoelectric layer and with a first voltage having a first polarity; and

a third electrode connected with the second side of the piezoelectric layer and with a second voltage having a second polarity opposite the first polarity, whereby said structure undergoes a substantially S-shaped deformation upon application of

15 said voltage.

16.

The structure of claim 15, further comprising a first contact pad and a second contact pad, wherein the structure operates as a switch, and wherein the first contact pad is
20 separated from the second contact pad when the switch is in a first condition chosen from an ON condition and an OFF condition, and the first contact pad contacts the second contact pad when the switch is in a second condition chosen from an ON condition and an OFF condition, different from the first condition.

25 17.

The structure of claim 16, wherein the first contact pad is located under the first electrode and the second contact pad is located on a substrate.

18.

30 The structure of claim 16 or claim 17, further comprising a support layer connected with the first electrode and the first contact pad.

19.

The structure of claim 15, further comprising a fourth electrode, connected with the substrate.

5

20.

A method of fabricating a micro electromechanical switch on a substrate comprising the steps of:

providing a substrate;

10

depositing a first metal layer on the substrate;

depositing a sacrificial layer on the substrate and on the first metal layer;

depositing a second metal layer on the sacrificial layer;

depositing a support layer on the sacrificial layer and the second metal layer;

depositing a third metal layer on the support layer;

15

depositing a first piezoelectric layer on the third metal layer;

depositing a fourth metal layer on the first piezoelectric layer;

patterning the fourth metal layer to form two separate metal layers on the first piezoelectric layer; and

removing the sacrificial layer.

20

21.

The method of claim 20, further comprising the steps of:

depositing a second piezoelectric layer on the fourth metal layer; and

depositing a fifth metal layer above the second piezoelectric layer.

25

22.

The method of claim 20 or claim 21, further comprising the step of etching the sacrificial layer, creating a hole in the sacrificial layer.

30

23.

The method of any one of claims 20-22, wherein the support layer is a Si_3N_4 layer.

24.

5 The method of any one of claims 20-23, wherein the step of depositing a first metal layer comprises a step of patterning the first metal layer to form a first contact pad of the switch and the step of depositing a second metal layer comprises the step of patterning the second metal layer to form a second contact pad of the switch, whereby a gap between the first contact pad and the second contact pad is formed upon removal of the sacrificial layer.

10 25.

A method of fabricating a micro electromechanical switch on a substrate, comprising the steps of:

15 providing a substrate;
depositing a first metal layer on the substrate;
depositing a sacrificial layer on the substrate and on the first metal layer;
depositing a support layer on the sacrificial layer;
depositing a second metal layer on the support layer and patterning the second metal layer to form a first contact pad;
20 depositing a separation layer on the support layer and the first contact pad;
depositing a third metal layer on the separation layer;
depositing a first piezoelectric layer on the third metal layer;
depositing a fourth metal layer on the first piezoelectric layer; and
removing the sacrificial layer.

25 26.

The method of claim 25, further comprising the step of patterning the fourth metal layer to form two separate metal layers above the first piezoelectric layer.

27.

30 The method of claim 25 or claim 26, wherein the support layer and the separation layer are made of Si_3N_4 .

28.

5 The method of any one of claims 25-27, further comprising the step of patterning the support layer to form a first support layer portion and a second support layer portion, the first contact pad being formed between the first support layer portion and the second support layer portion.

29.

10 The method of claim 28, wherein, after the step of forming the first contact pad and before the step of removing the sacrificial layer, the first contact pad is partially recessed in the sacrificial layer.

30.

15 The method of any one of claims 25-29, further comprising the steps of:
depositing a second piezoelectric layer above the fourth metal layer; and
depositing a fifth metal layer above the second piezoelectric layer.

31.

20 The method of any one of claims 25-30, wherein the step of depositing a first metal layer comprises a step of patterning the first metal layer to form a second contact pad, wherein a gap between the first contact pad and the second contact pad is formed upon removal of the sacrificial layer.

25 32.

A micro electromechanical switch formed on a substrate comprising:

an upper piezoelectric layer;
a lower piezoelectric layer;
a first electrode placed under the lower piezoelectric layer;
30 a second electrode placed between the upper piezoelectric layer and the lower piezoelectric layer; and a
third electrode placed on the upper piezoelectric layer.

33.

The switch of claim 32, further comprising a support layer connected with the first electrode.

5

34.

The switch of claim 33, wherein the support layer is a Si_3N_4 layer.

35.

10 The switch of any one of claims 32-34, wherein a spacer separates the switch from the substrate.

36.

15 The switch of any one of claims 32-35, further comprising a first contact pad located under the lower piezoelectric layer and a second contact pad connected with the substrate.

37.

20 The switch of claim 36, wherein the first and second contact pad are chosen from the group consisting of gold, platinum, titanium-platinum or titanium-gold.

38.

25 The switch of claim 36 or claim 37, wherein the first contact pad is positioned so as to face the second contact pad.

39.

30 The switch of any one of claims 36-38, wherein the first contact pad is separated from the second contact pad when the switch is in a first condition chosen from an ON condition and an OFF condition and the first contact pad contacts the second contact pad when the switch is in a second condition chosen from an ON condition and an OFF condition, different from the first condition.

40.

The switch of claim 39, wherein the switch undergoes a substantially S-shaped deformation when the first contact pad contacts the second contact pad.

5

41.

The switch of claim 39 or claim 40, wherein the distance between the first contact pad and the second contact pad when the switch is in said first condition is about 1 micron.

10 42.

A micro electromechanical switch formed on a substrate and operating under a combined piezoelectric and electrostatic effect, the switch comprising:

a first piezoelectric layer;

a second piezoelectric layer;

15 a first electrode placed under the second piezoelectric layer;

a second electrode placed between the first piezoelectric layer and the second piezoelectric layer;

a third electrode placed on the first piezoelectric layer; and

a fourth electrode placed on the substrate.

20

43.

The switch of claim 42, further comprising a support layer connected with the first electrode.

25 44.

The switch of claim 42 or claim 43, further comprising a first contact pad located under the second piezoelectric layer and a second contact pad connected with the substrate, the first contact pad being positioned so as to face the second contact pad.

30 45.

The switch of claim 44, wherein the first contact pad is separated from the second contact pad when the switch is in a first condition chosen from an ON condition and an

OFF condition and the first contact pad contacts the second contact pad when the switch is in a second condition chosen from an ON condition and an OFF condition, different from the first condition.

5 46.

The switch of any one of claims 42-45, wherein at least one of the first, second and third electrodes is T-shaped.

47.

10 The switch of claim 45 or claim 46, wherein the first electrode is connected to a voltage having a first polarity and the second electrode is connected to a voltage having a second polarity opposite the first polarity, and wherein the switch undergoes a substantially S-shaped deformation when the first contact pad contacts the second contact pad.

15

48.

A method of fabricating a micro electromechanical switch on a substrate comprising the steps of:

providing a substrate;

20

depositing a first metal layer on the substrate;

patterning the first metal layer to form two separate metal layers on the substrate;

depositing a sacrificial layer on the substrate and on the two separate metal layers;

25

depositing a second metal layer on the sacrificial layer;

depositing a support layer on the second metal layer and the sacrificial layer;

depositing a third metal layer on the support layer;

depositing a first piezoelectric layer on the third metal layer;

depositing a fourth metal layer on the first piezoelectric layer; and

30

removing the sacrificial layer.

49.

The method of claim 48, further comprising the step of patterning the sacrificial layer to form a hole therein.

5 50.

The method of claim 48 or claim 49, further comprising the step of:
patterning the fourth metal layer to form two separate metal layers.

51.

10 The method of any one of claims 48-50, further comprising the steps of:
depositing a second piezoelectric layer on the fourth metal layer; and
depositing a fifth metal layer above the second piezoelectric layer.

52.

15 A method of fabricating a micro electromechanical switch on a substrate, comprising the steps of:

providing a substrate;

depositing a first metal layer on the substrate;

20 patterning the first metal layer to form two separate metal layers on the substrate;

depositing a sacrificial layer on the substrate and on the two separate metal layers;

depositing a support layer on the sacrificial layer;

25 depositing a second metal layer on the support layer and patterning the second metal layer to form a first contact pad;

depositing a separation layer on the support layer and the first contact pad;

depositing a third metal layer on the separation layer;

depositing a first piezoelectric layer on the third metal layer;

30 depositing a fourth metal layer on the first piezoelectric layer; and removing the sacrificial layer.

53.

The method of claim 52, further comprising the step of:

patterning the fourth metal layer to form two separate metal layers.

5 54.

The method of claim 52 or claim 53, wherein the support layer and the separation layer are made of Si_3N_4 .

55.

10 The method of any one of claims 52-54, further comprising the steps of:

depositing a second piezoelectric layer on the fourth metal layer; and
depositing a fifth metal layer on the second piezoelectric layer.

56.

15 The method of any one of claims 52-55, further comprising the step of patterning the support layer to form a first support layer portion and a second support layer portion, the first contact pad being formed between the first support layer portion and the second support layer portion.

20 57.

The method of claim 56, wherein, after the step of forming the first contact pad and before the step of removing the sacrificial layer, the first contact pad is partially recessed in the sacrificial layer.

25 58.

The method of any one of claims 52-57, wherein the step of depositing a first metal layer comprises a step of patterning the first metal layer to form a second contact pad, wherein a gap between the first contact pad and the second contact pad is formed upon removal of the sacrificial layer.

30

59.

A micro electromechanical switch formed on a substrate and operating under a combined piezoelectric and electrostatic effect, the switch comprising:

a first piezoelectric layer;

a second piezoelectric layer;

a first electrode placed under the second piezoelectric layer;

a second electrode and a third electrode placed between the first piezoelectric layer and the second piezoelectric layer;

a fourth electrode placed on the first piezoelectric layer; and

a fifth electrode placed on the substrate.

60.

The switch of claim 59, further comprising a support layer connected with the first electrode.

61.

The switch of claim 59 or claim 60, further comprising a first contact pad located under the second piezoelectric layer and a second contact pad connected with the substrate, the first contact pad being positioned so as to face the second contact pad.

62.

The switch of claim 61, wherein the first contact pad is separated from the second contact pad when the switch is in a first condition chosen from an ON condition and an OFF condition and the first contact pad contacts the second contact pad when the switch is in a second condition chosen from an ON condition and an OFF condition, different from the first condition.

63.

The switch of any one of claims 59-62, wherein the second electrode is connected to a voltage having a first polarity and the third electrode is connected to a voltage having a second polarity opposite the first polarity, and wherein the switch undergoes a substantially S-shaped deformation when the first contact pad contacts the second contact pad.

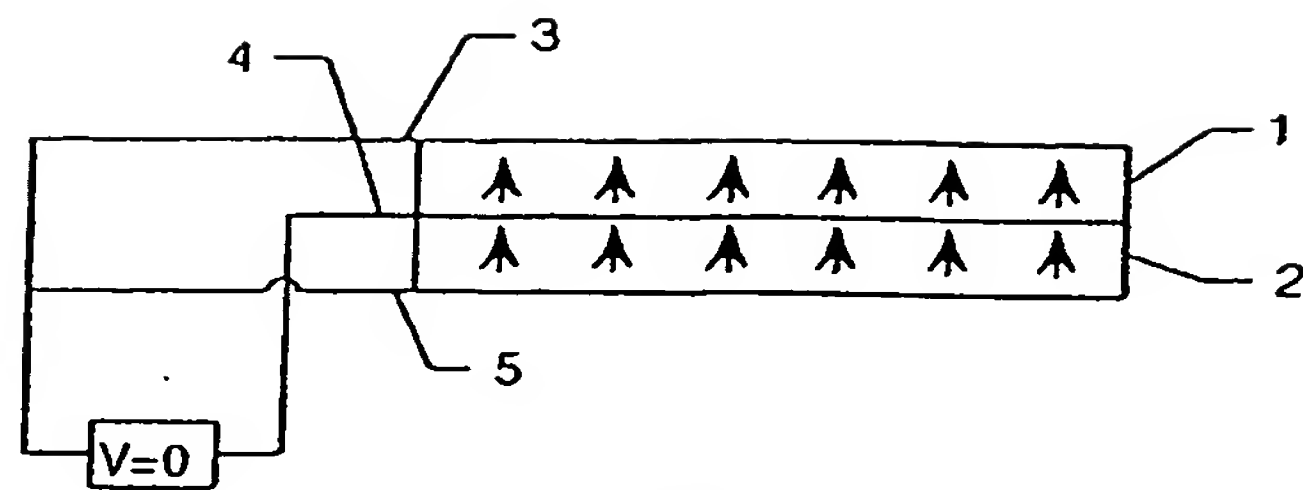


FIG. 1a

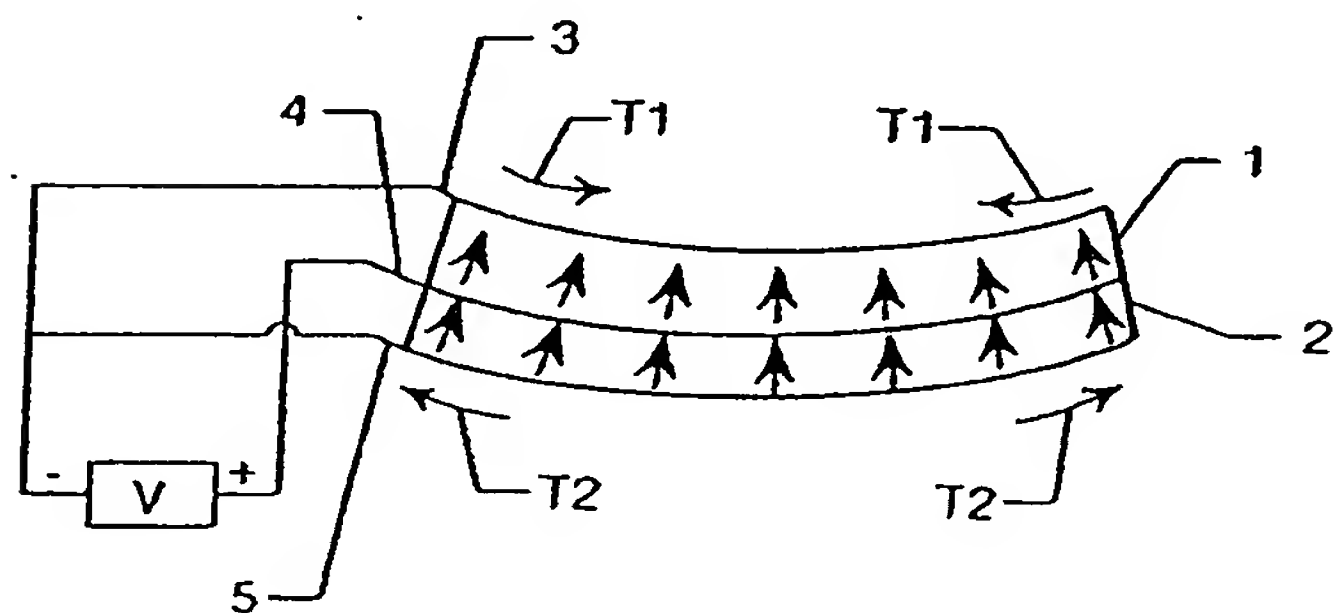


FIG. 1b

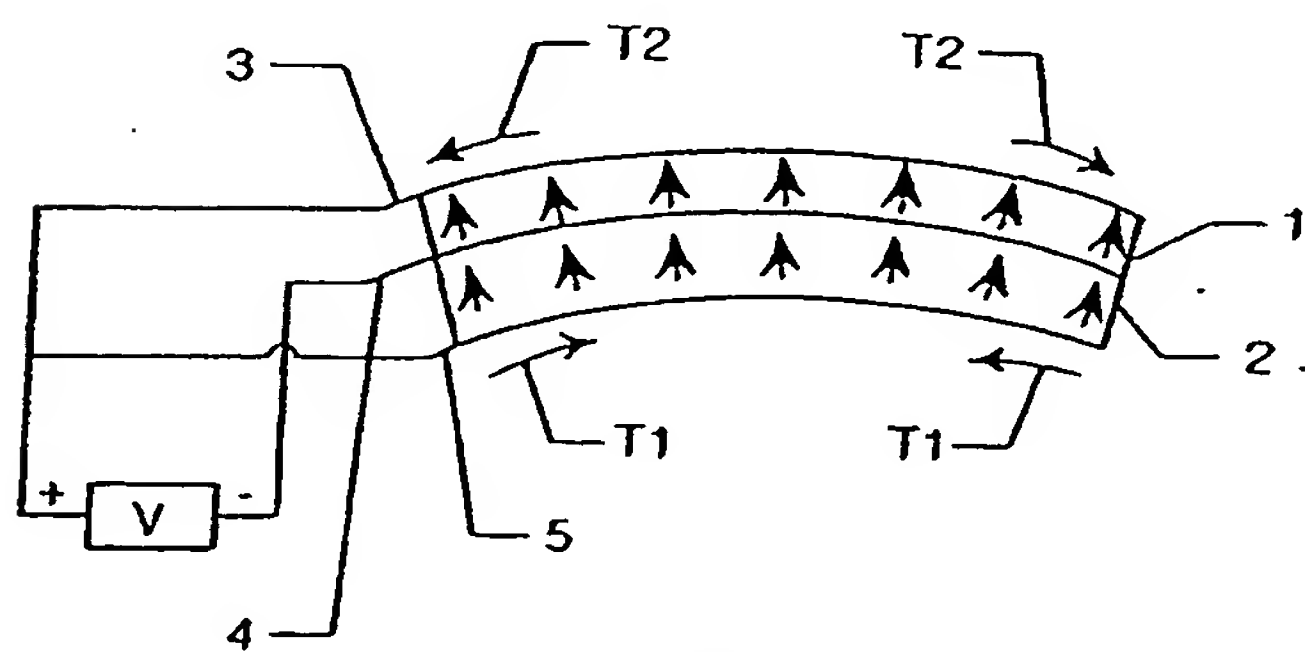


FIG. 1c

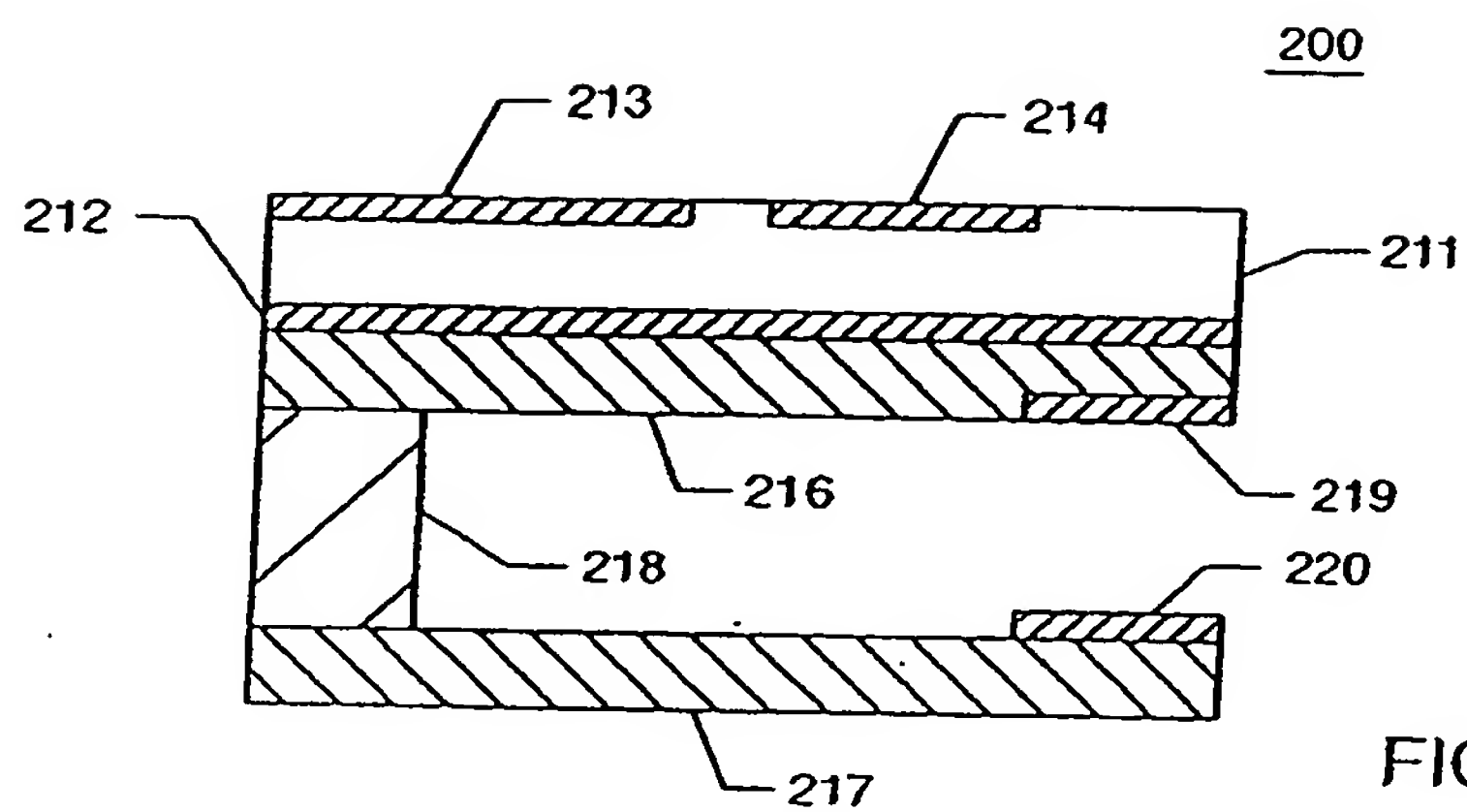


FIG. 3A

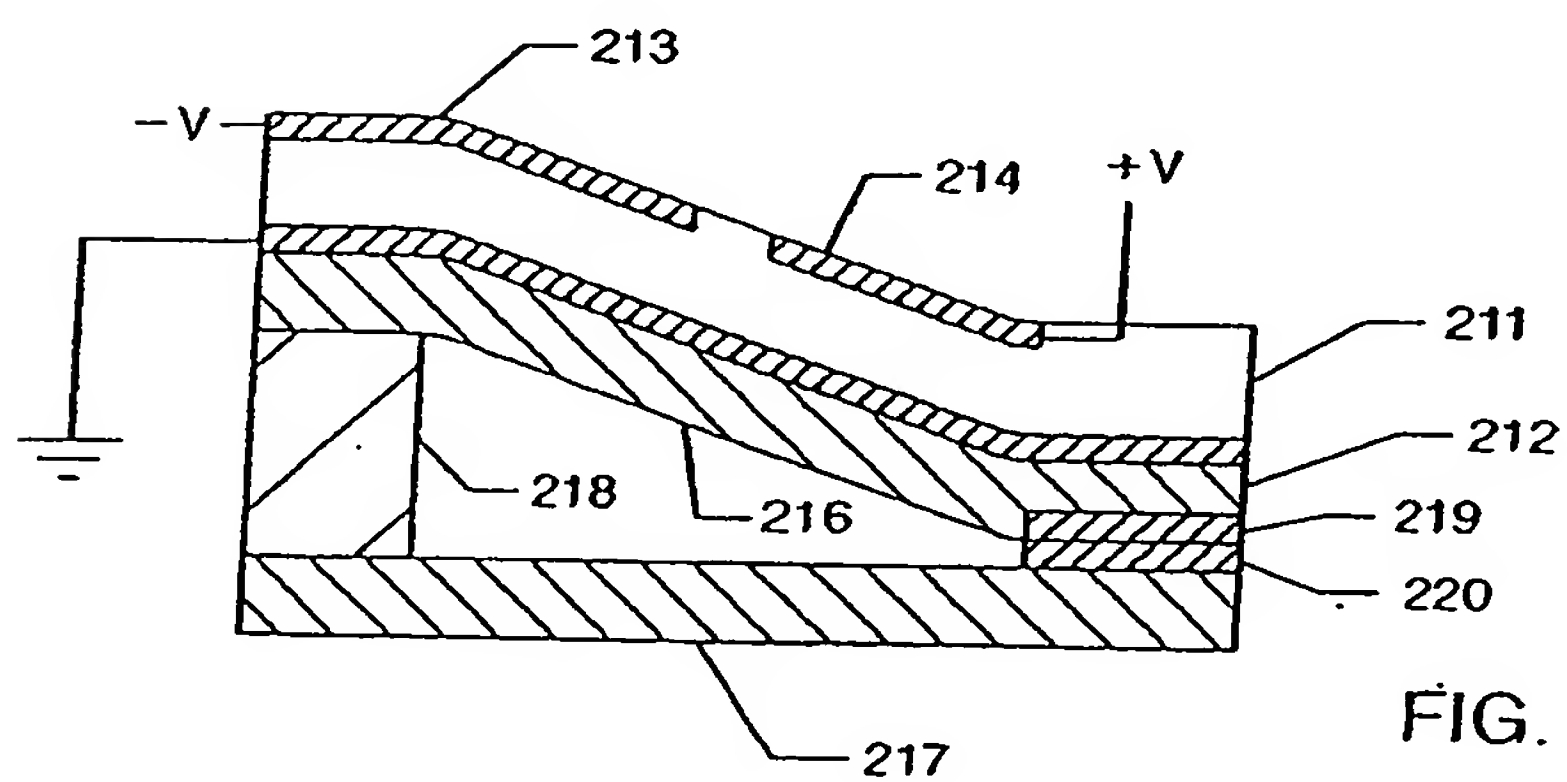


FIG. 3B

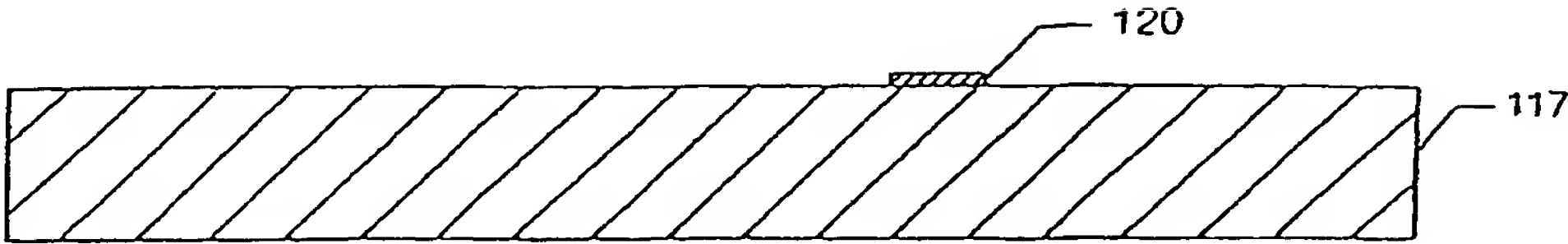


FIG. 4A

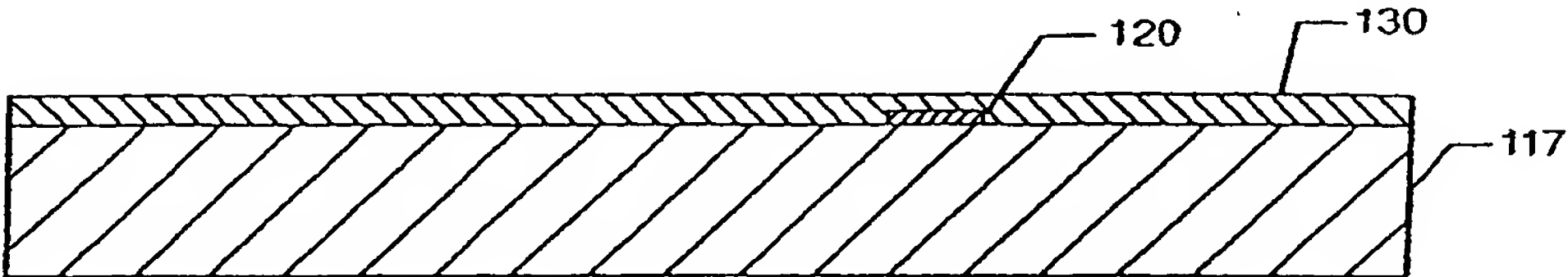


FIG. 4B

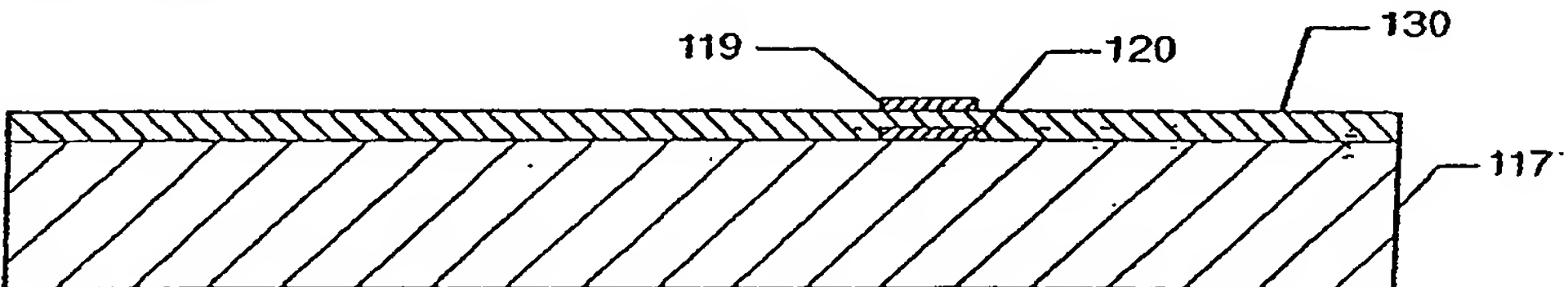


FIG. 4C

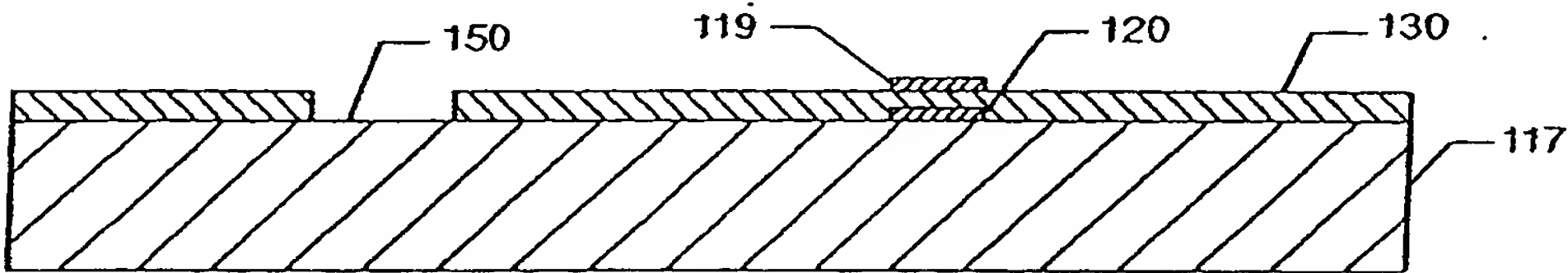


FIG. 4D

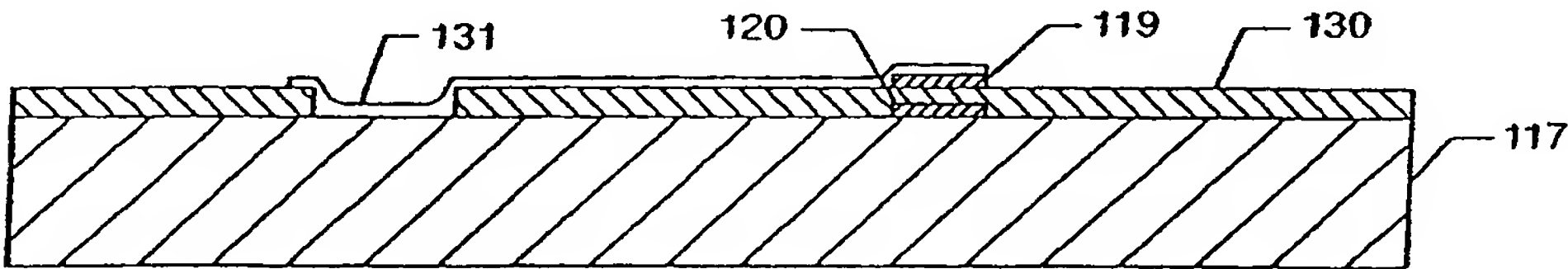


FIG. 4E

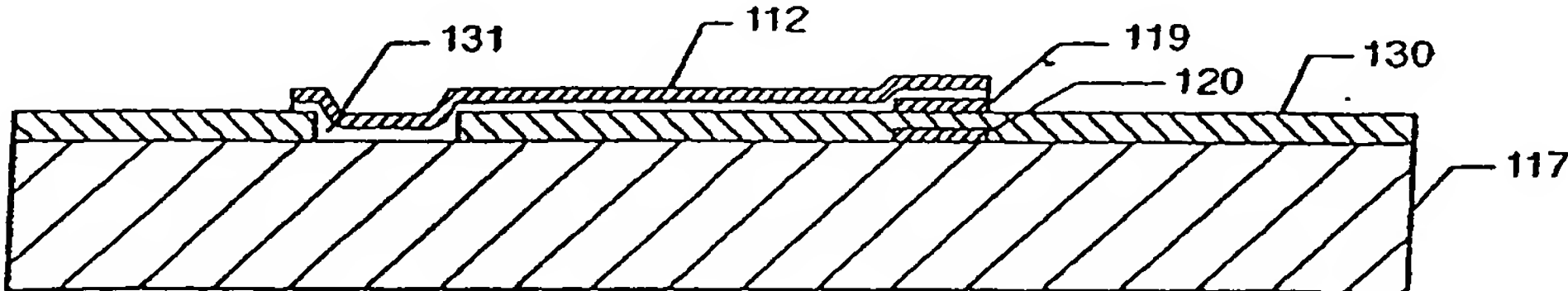


FIG. 4F

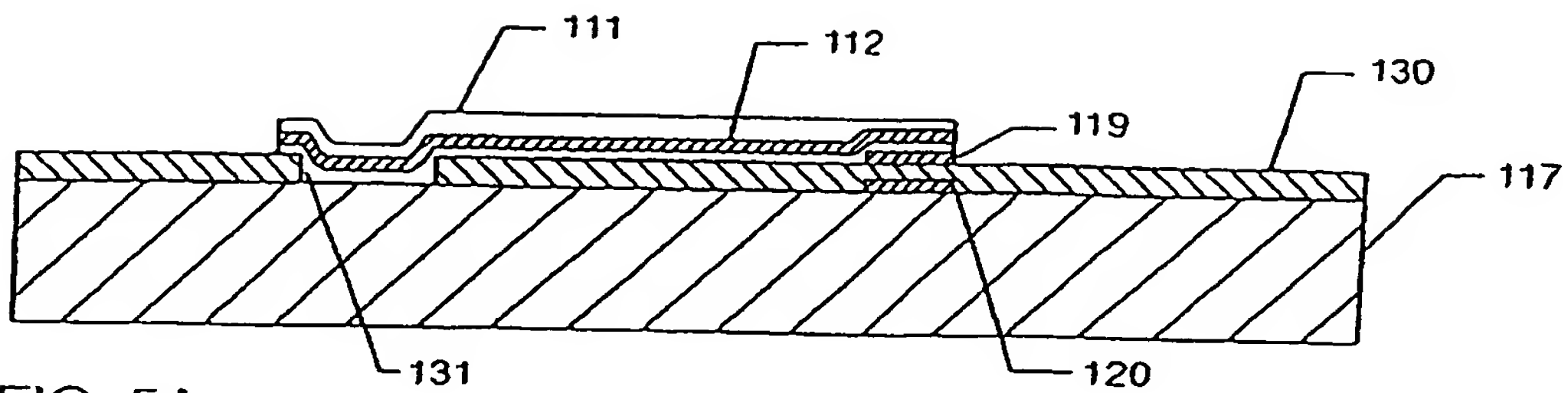


FIG. 5A

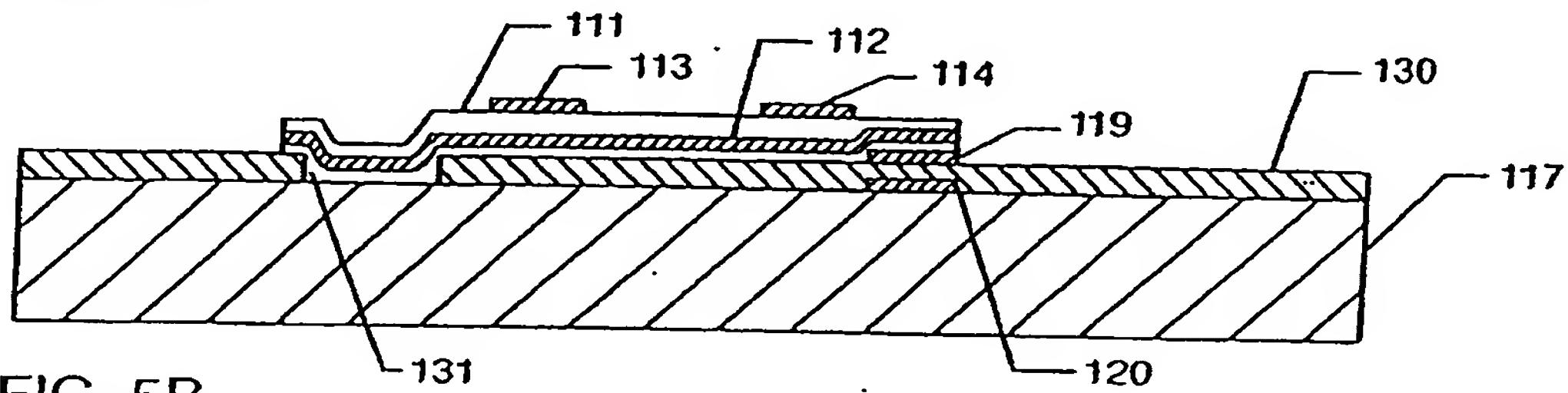


FIG. 5B

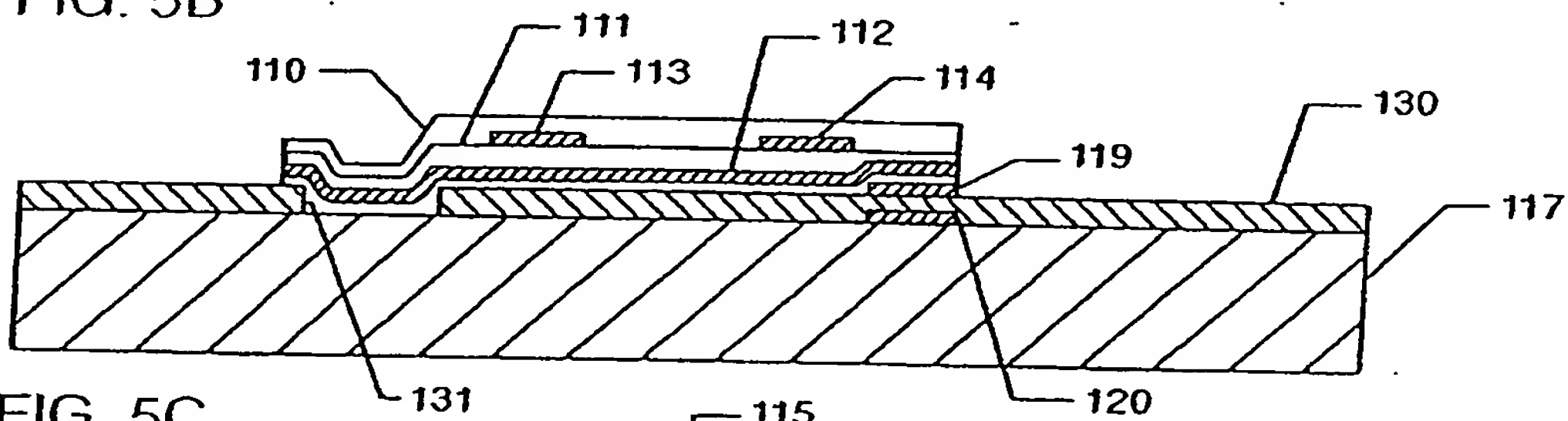


FIG. 5C

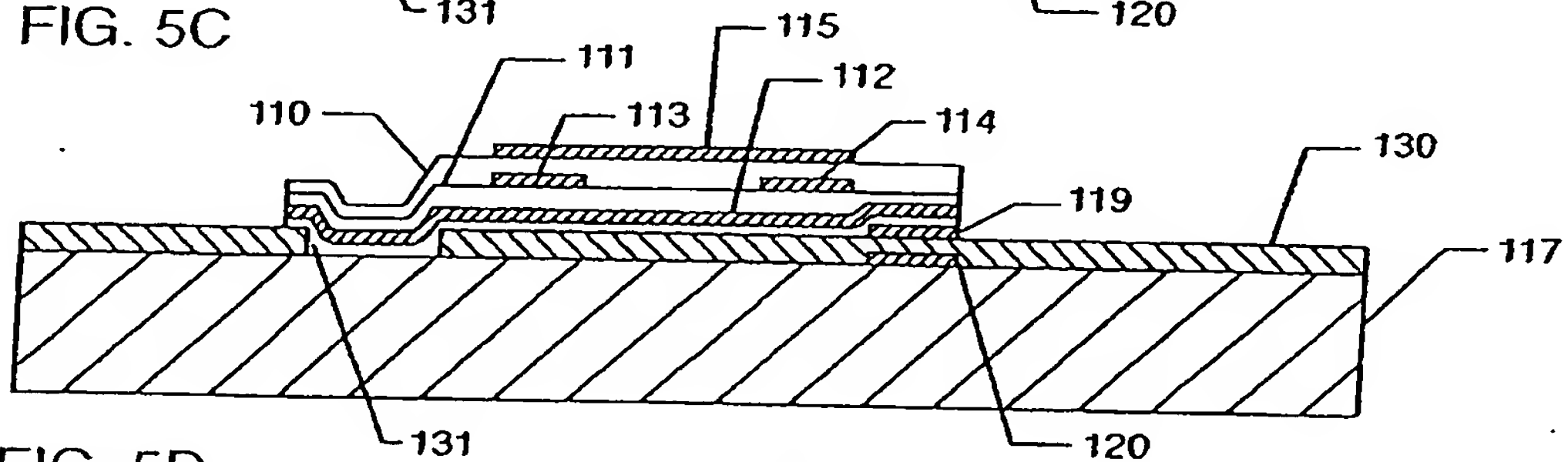


FIG. 5D

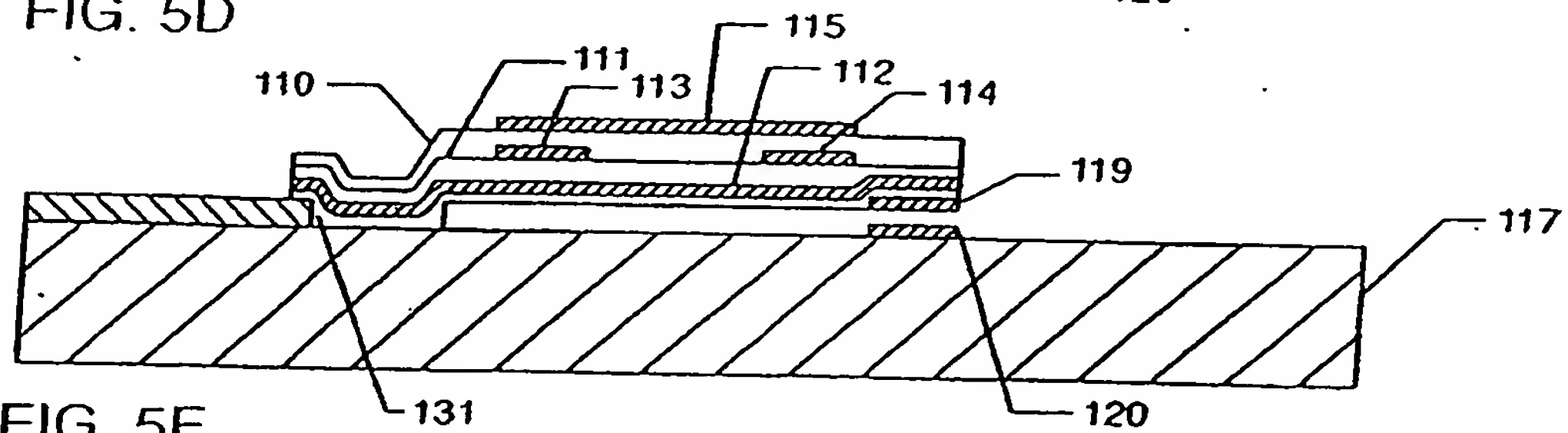


FIG. 5E

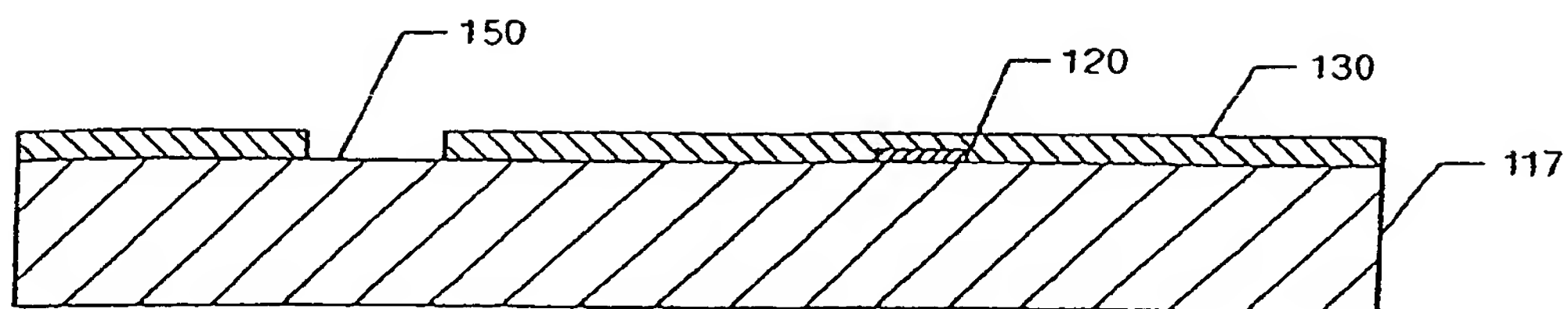


FIG. 6A

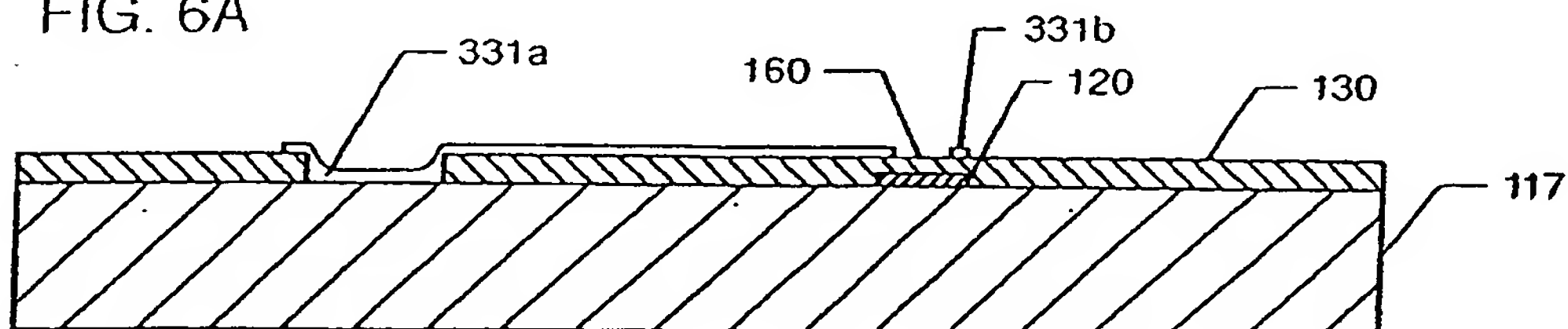


FIG. 6B

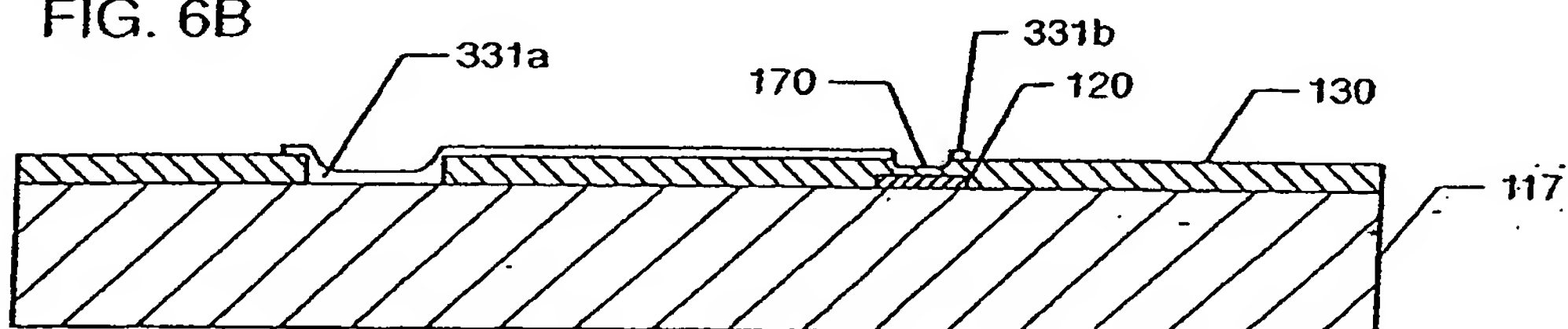


FIG. 6C

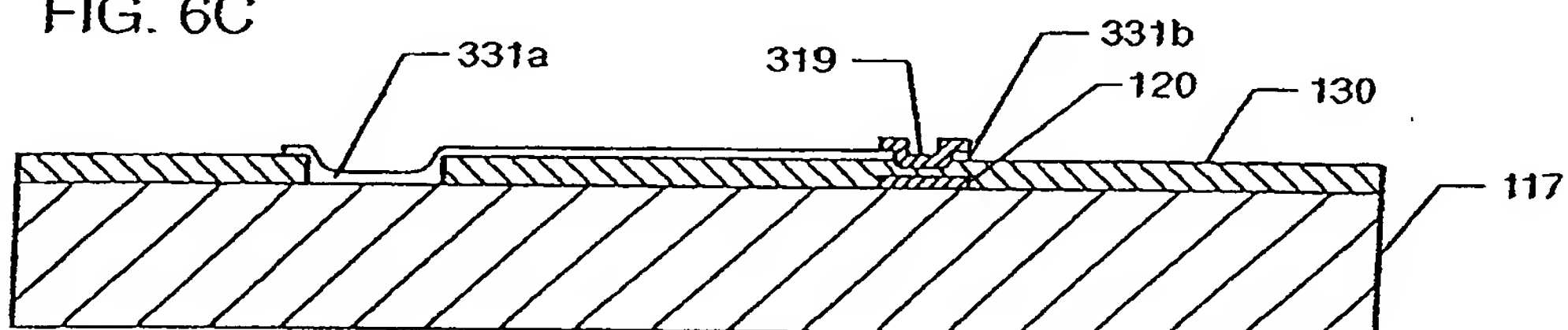


FIG. 6D

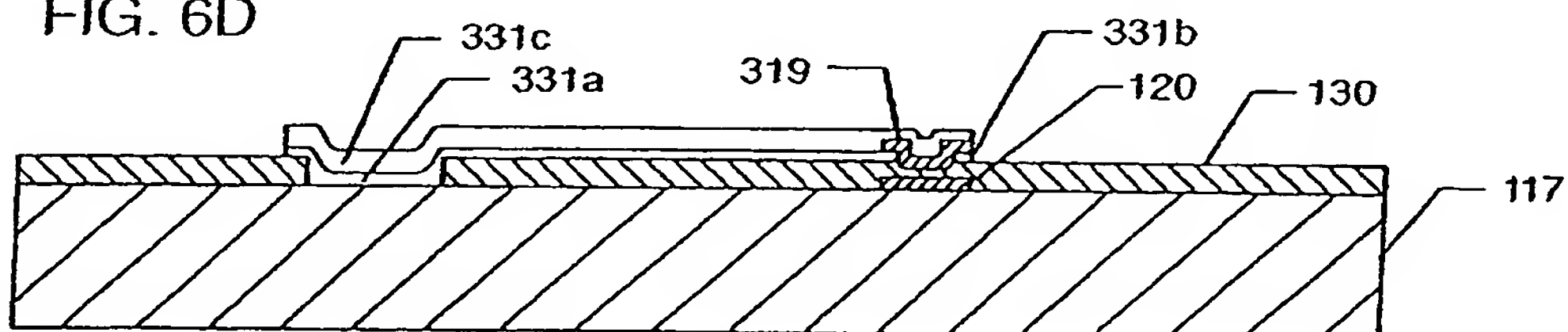


FIG. 6E

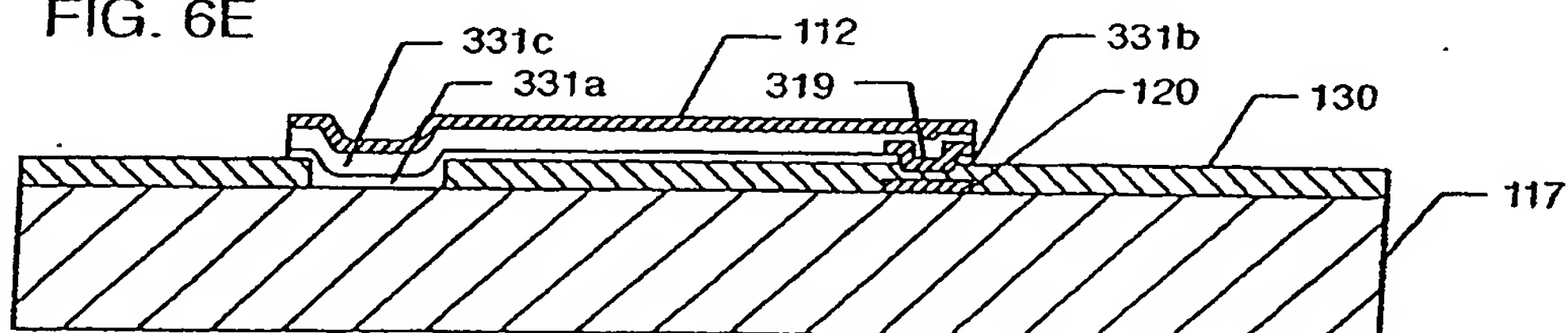


FIG. 6F

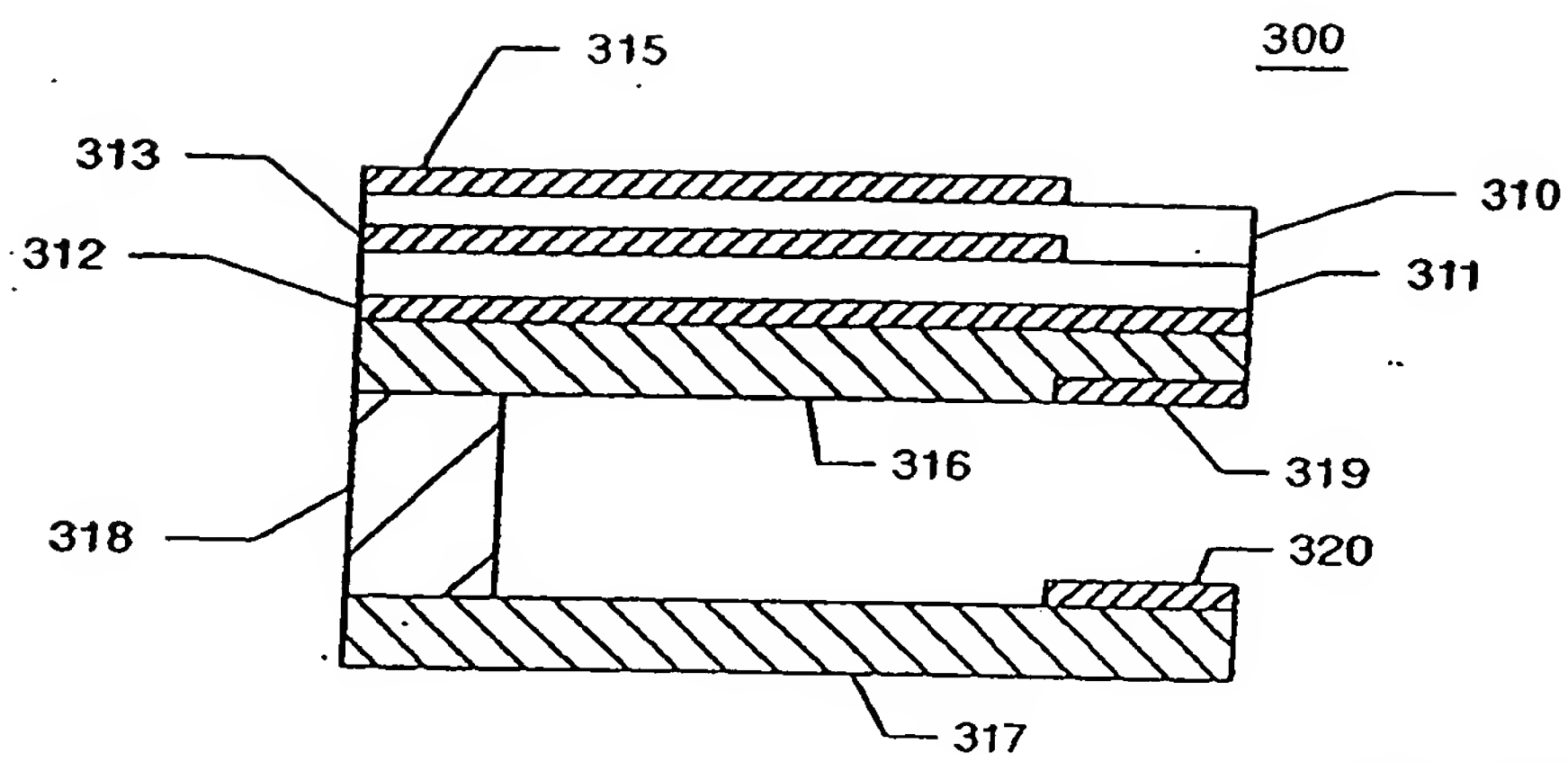


FIG. 7A

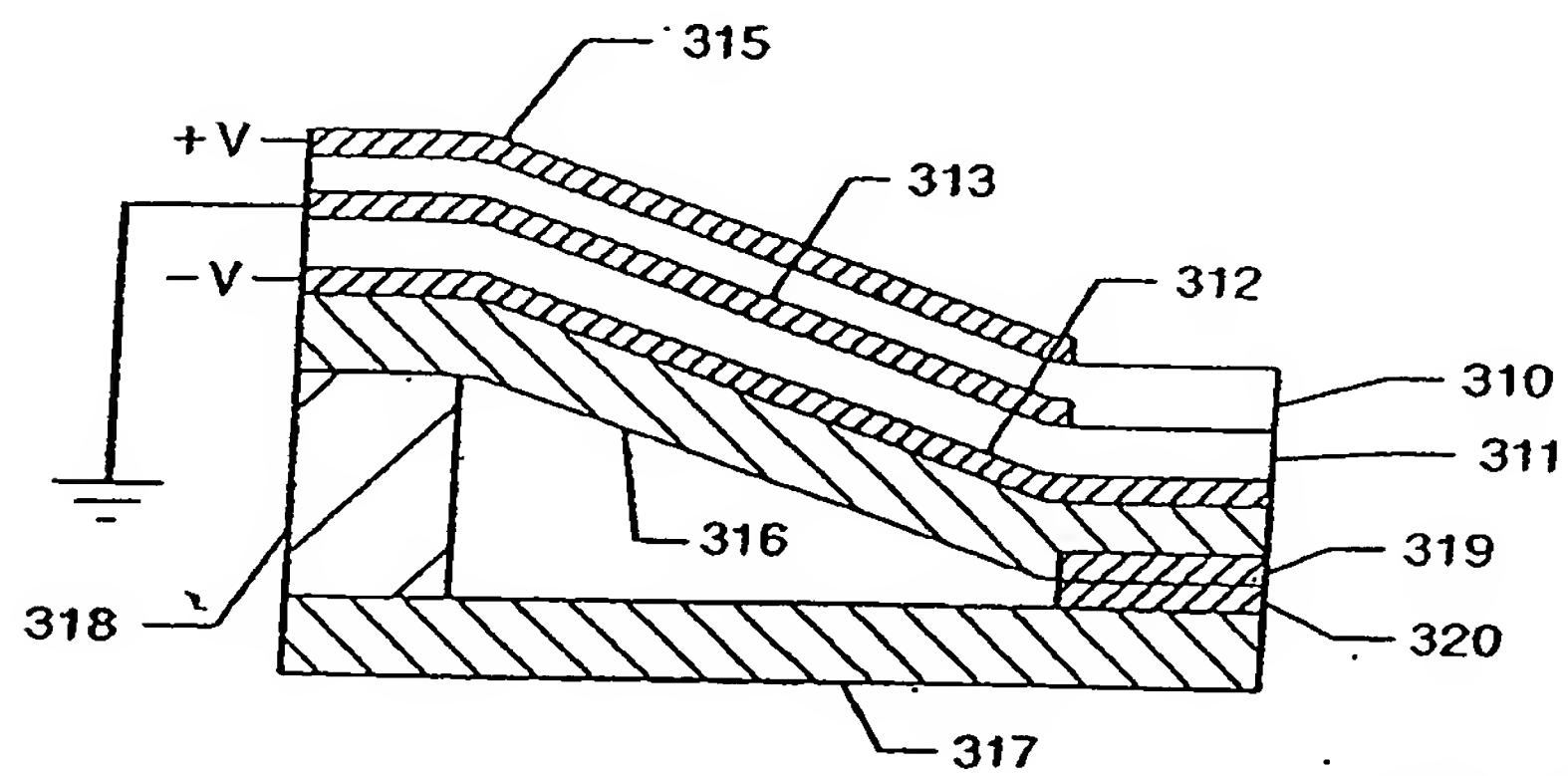
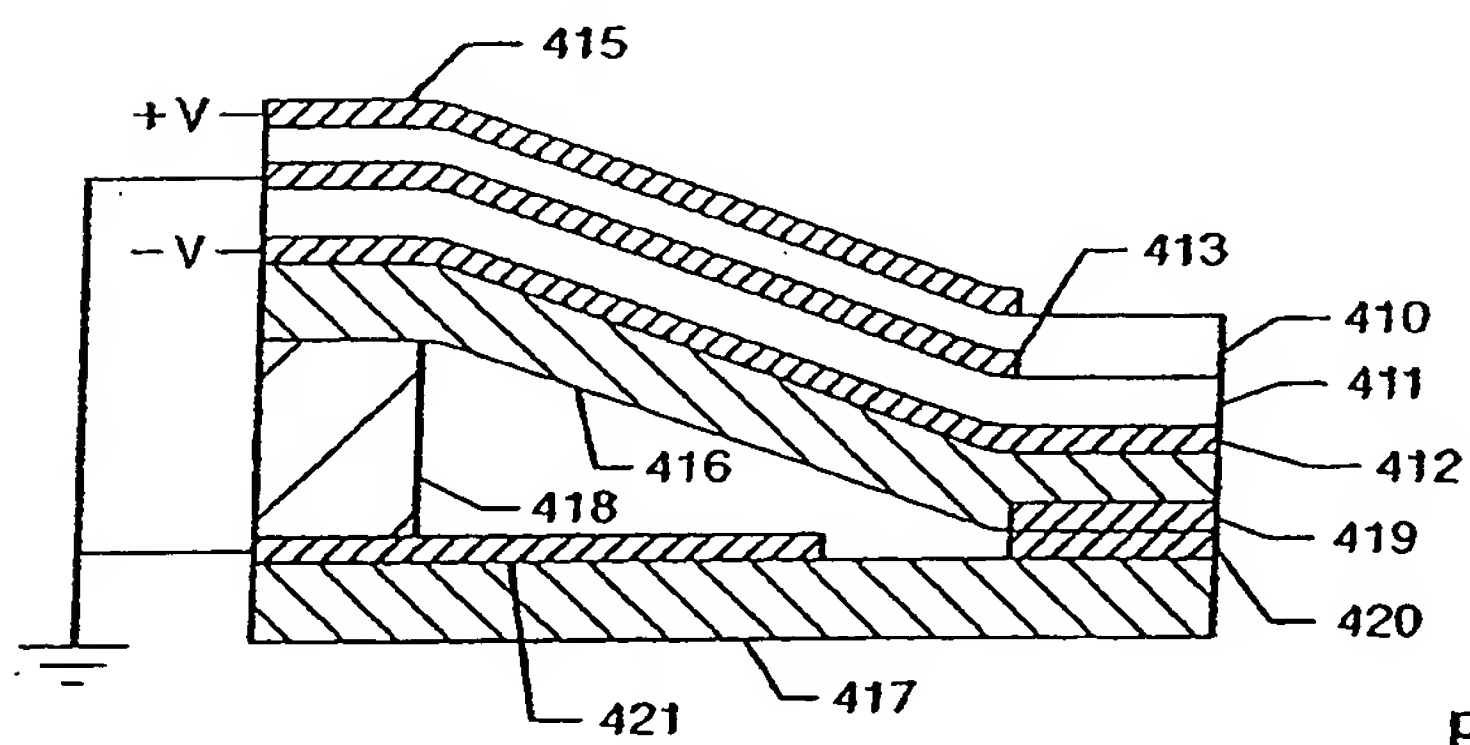
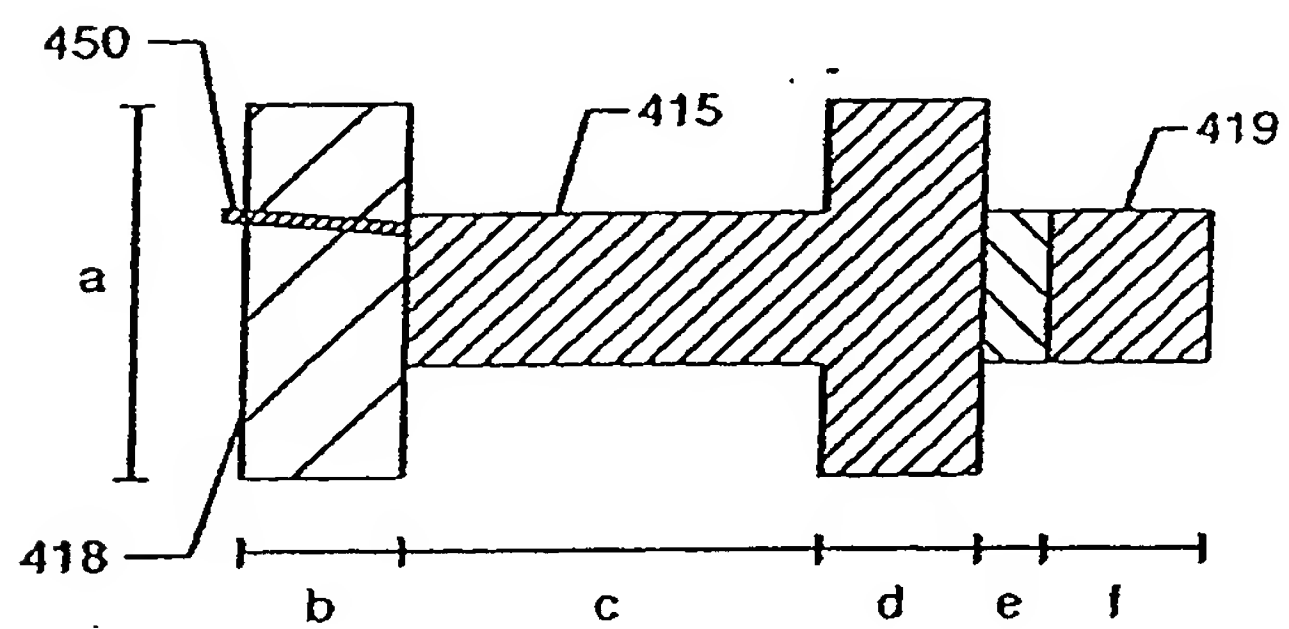
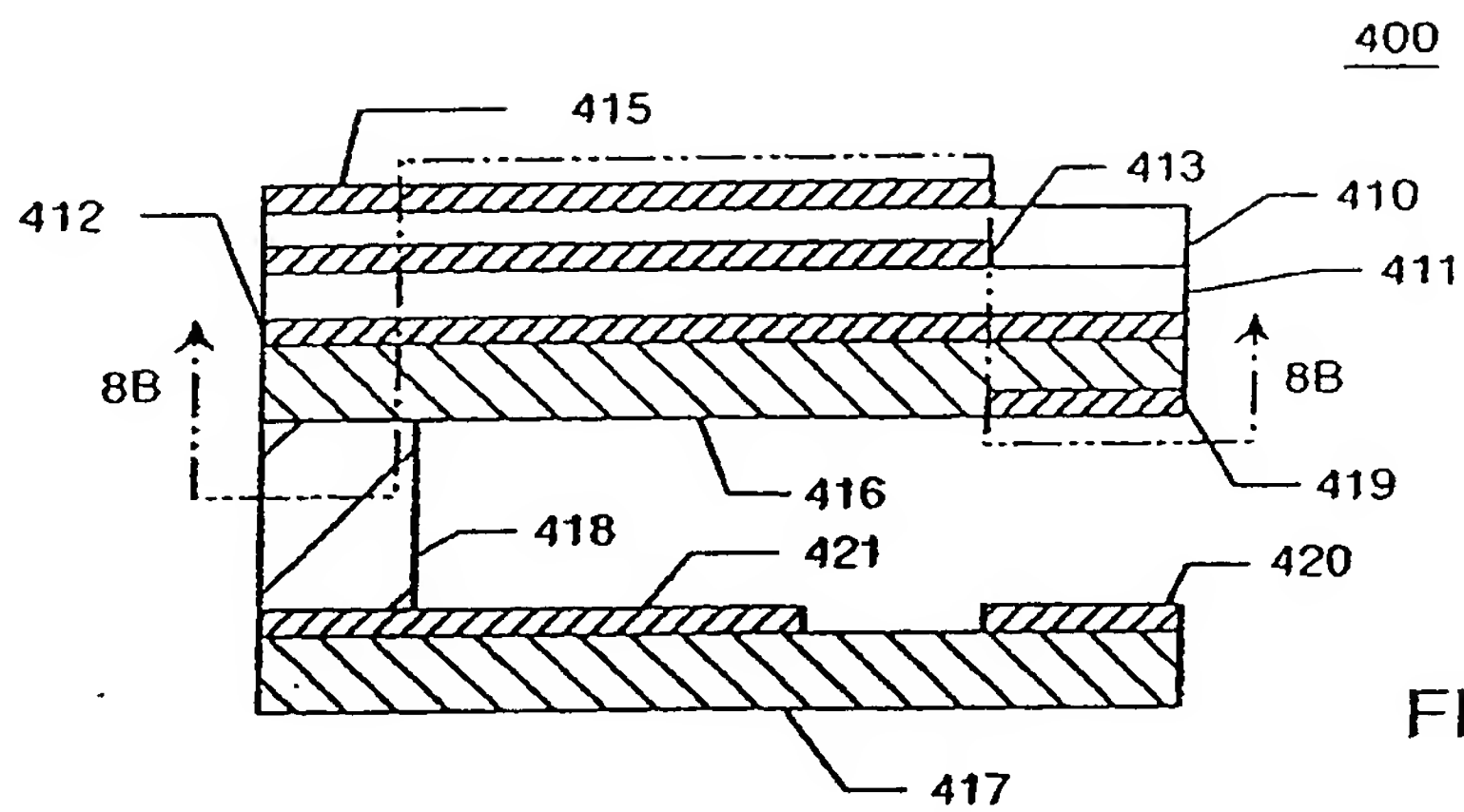


FIG. 7B



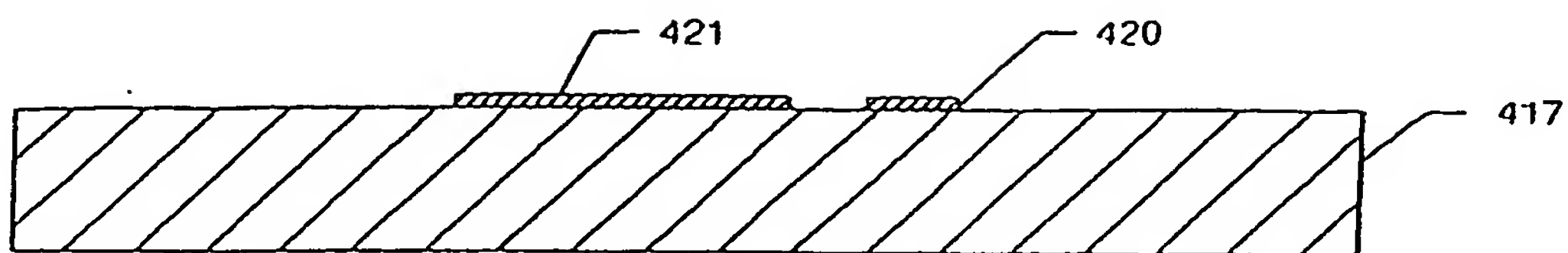


FIG. 9A

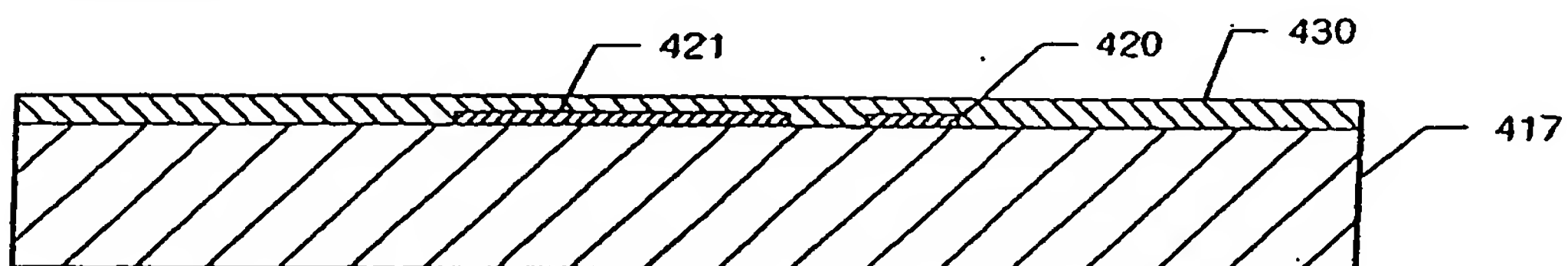


FIG. 9B

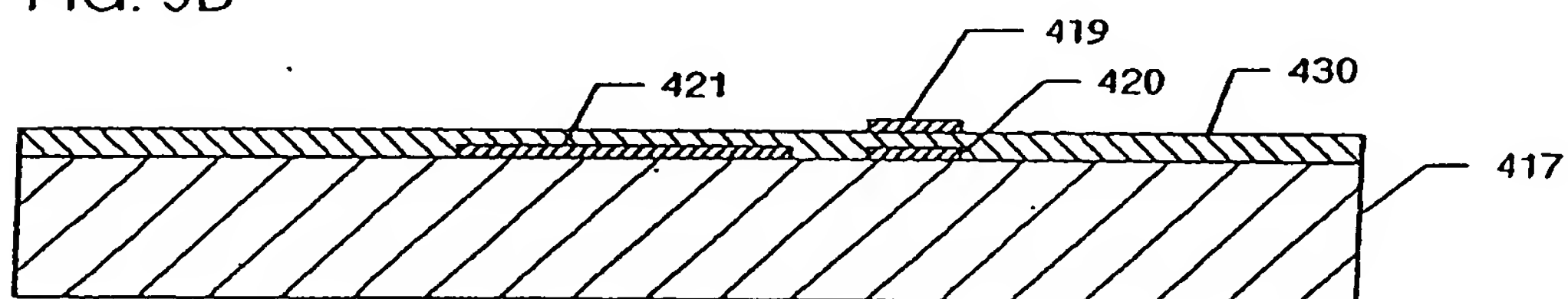


FIG. 9C

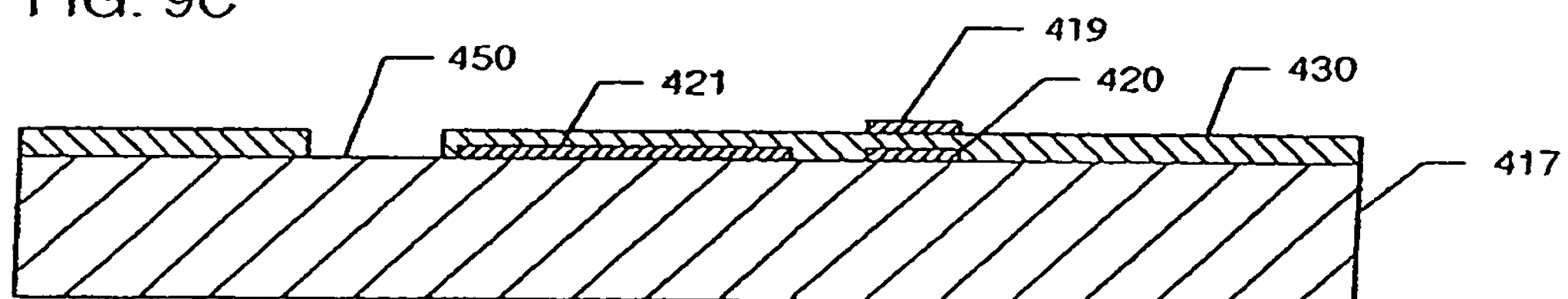


FIG. 9D

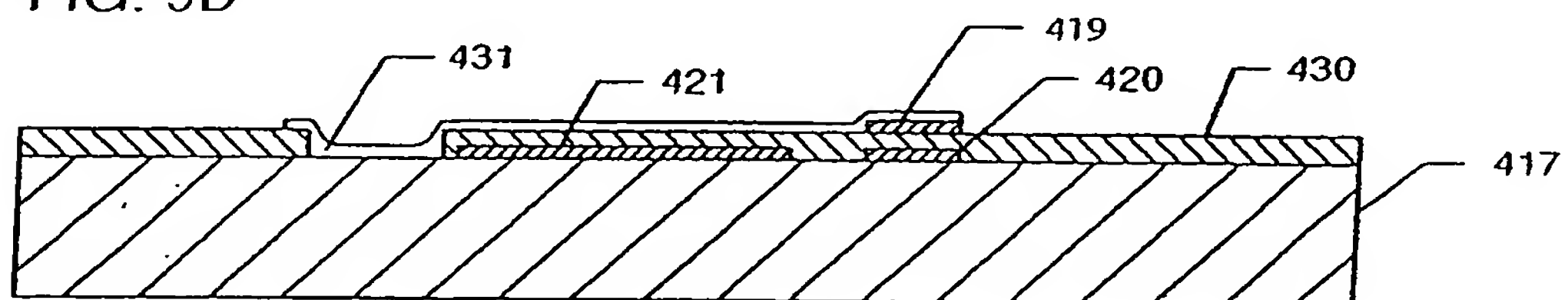


FIG. 9E

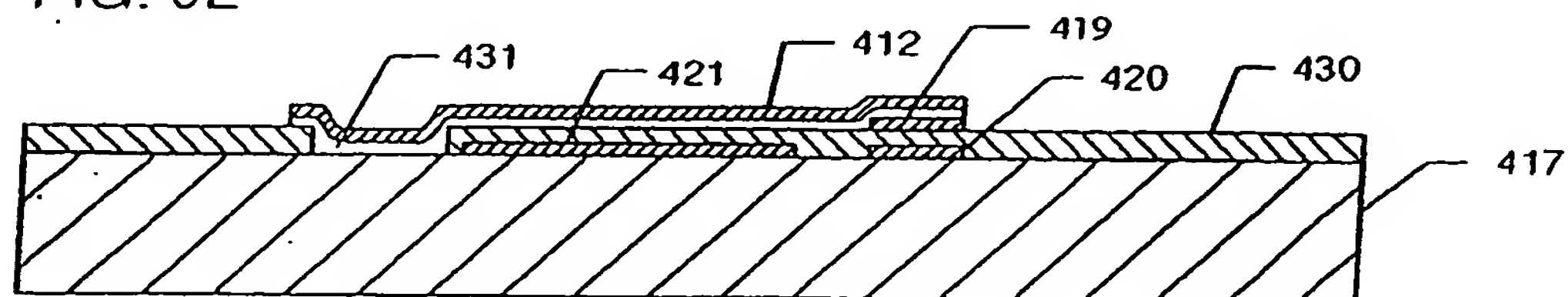


FIG. 9F

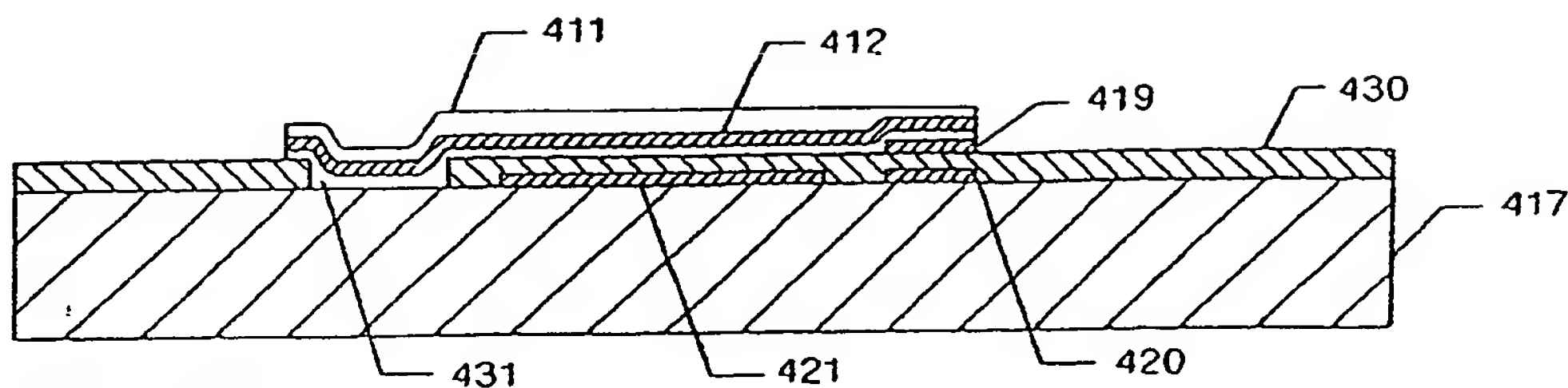


FIG. 10A

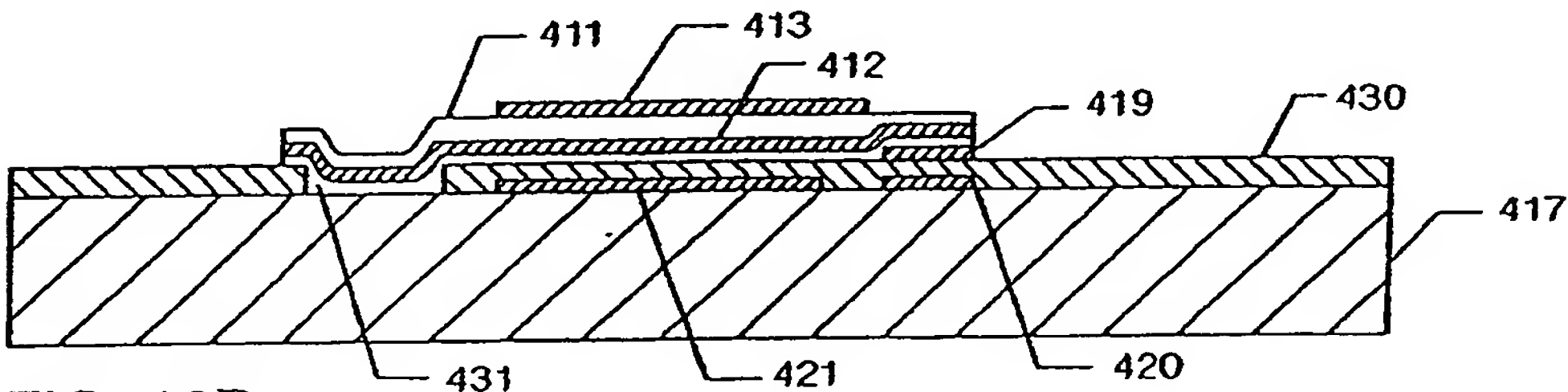


FIG. 10B

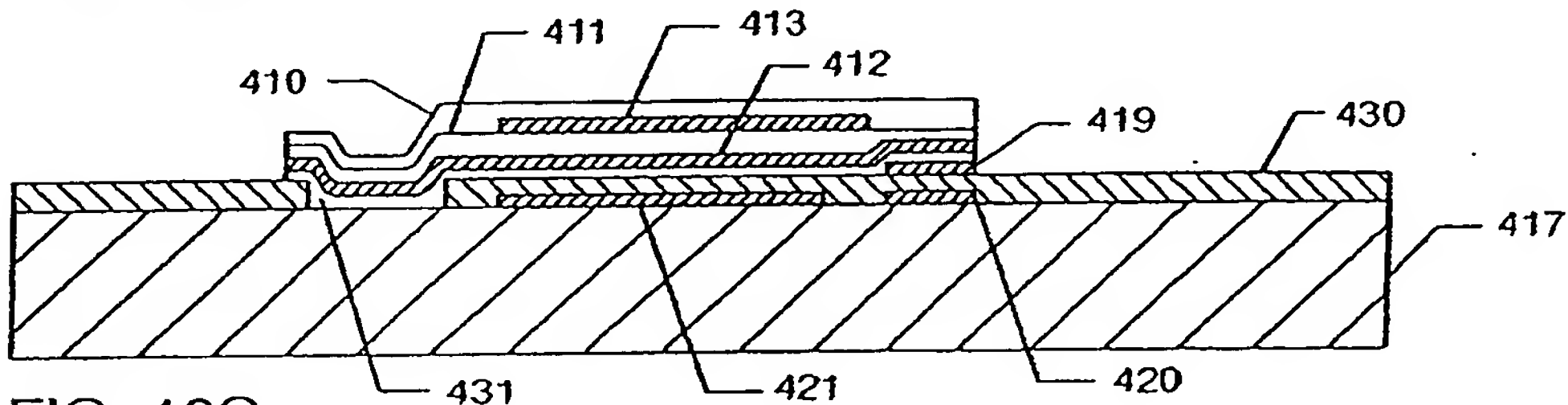


FIG. 10C

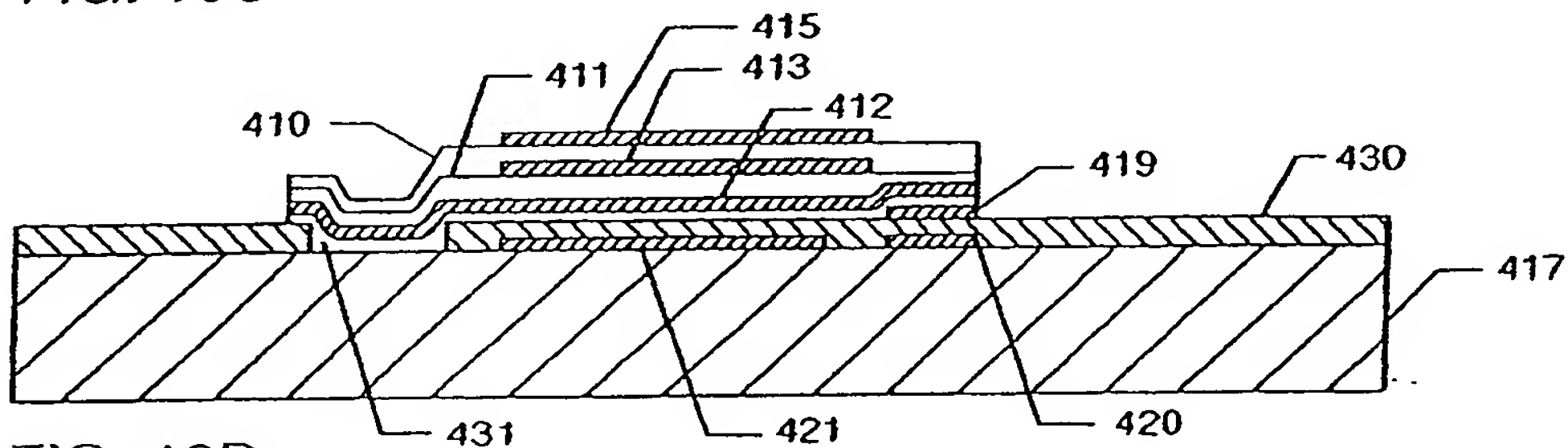


FIG. 10D

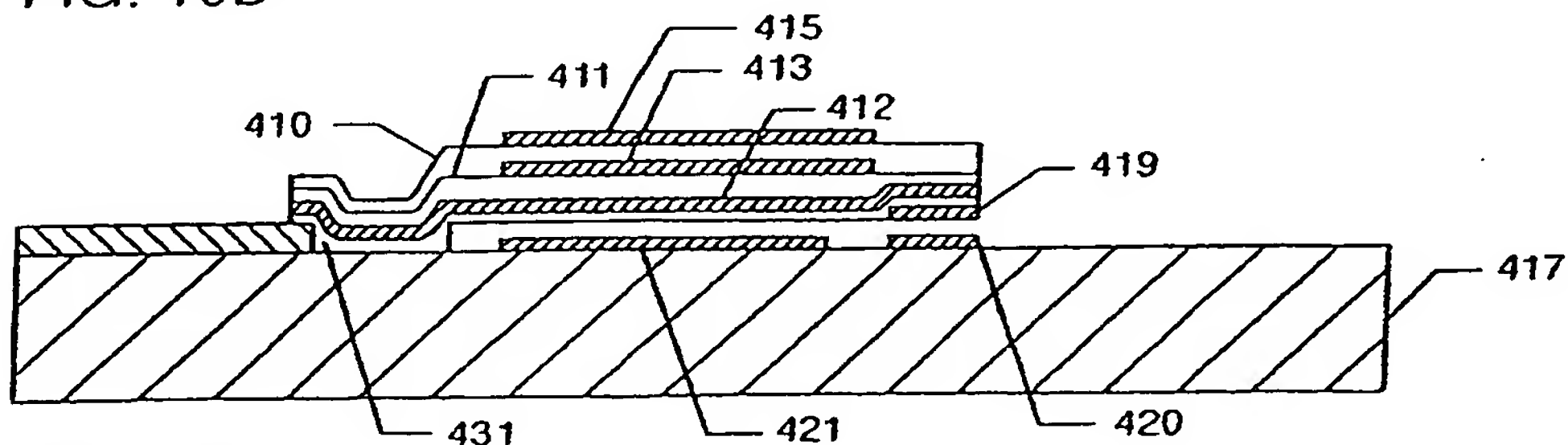


FIG. 10E

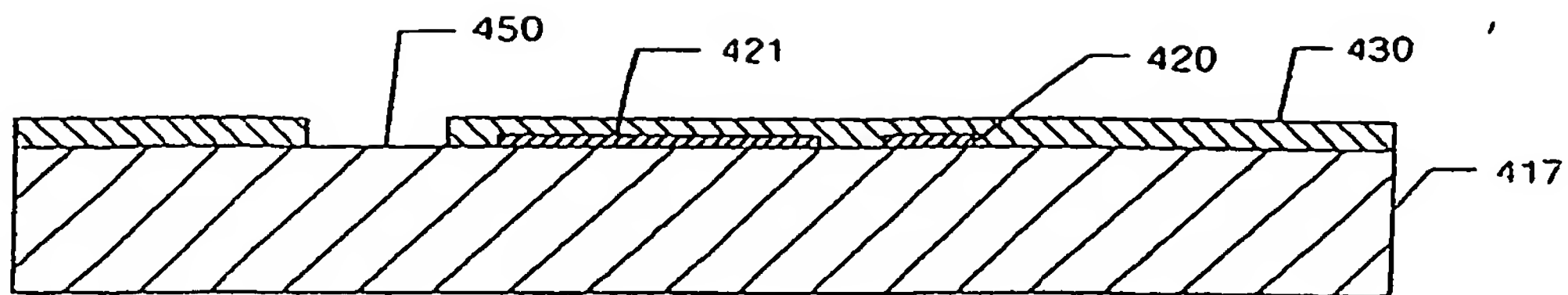


FIG. 11A

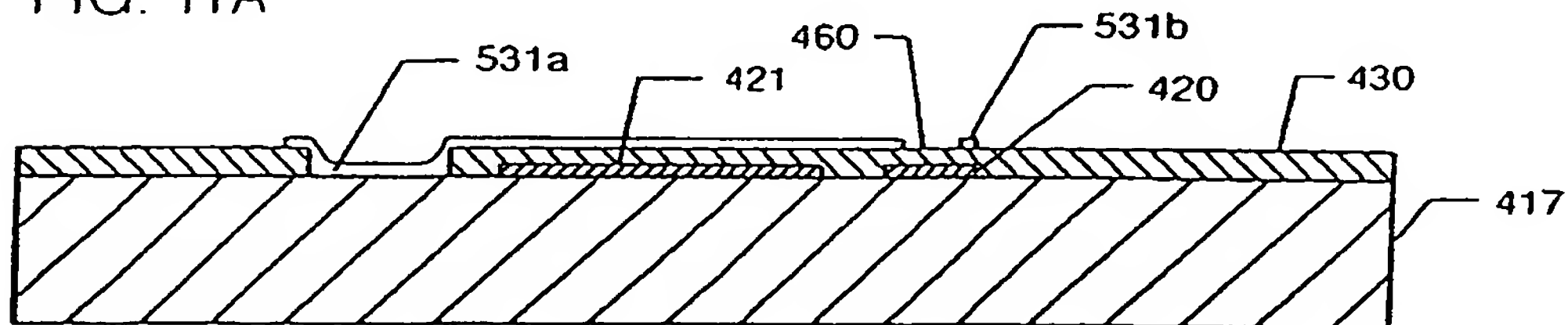


FIG. 11B

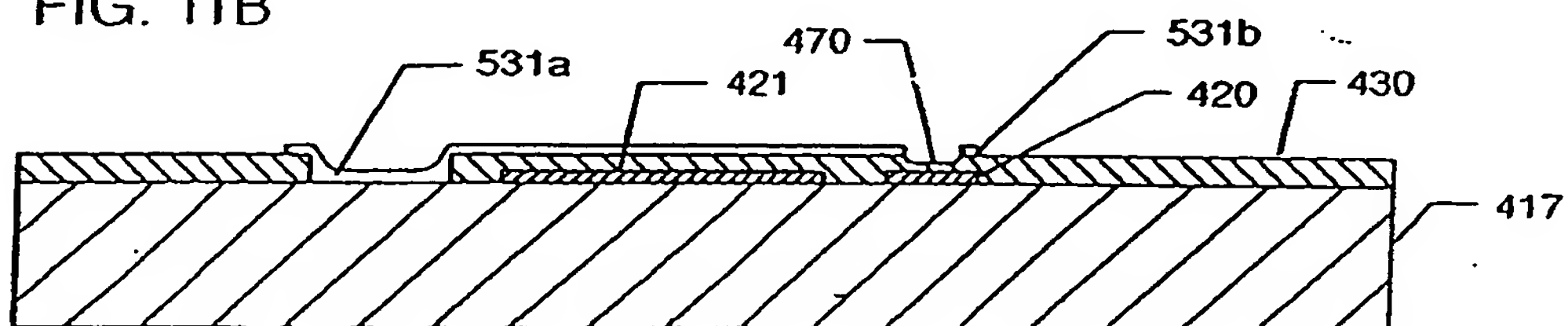


FIG. 11C

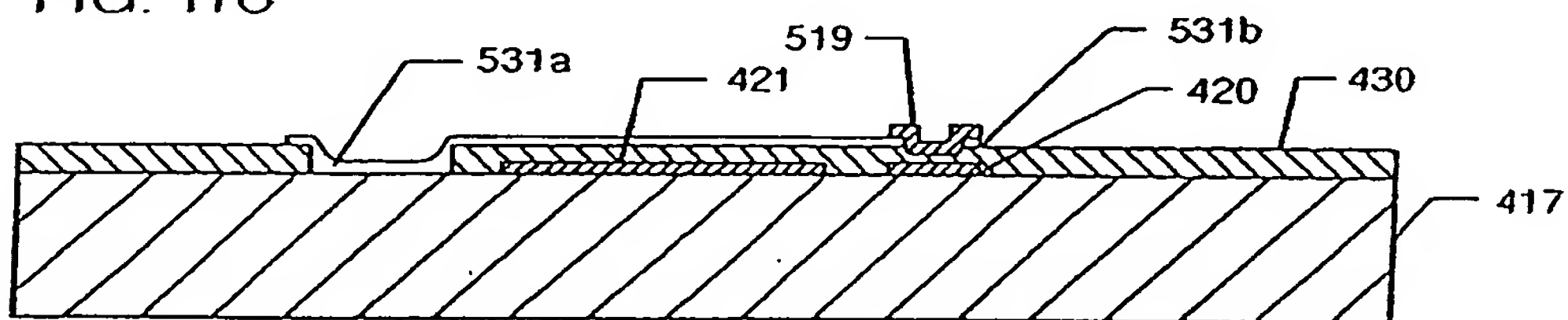


FIG. 11D

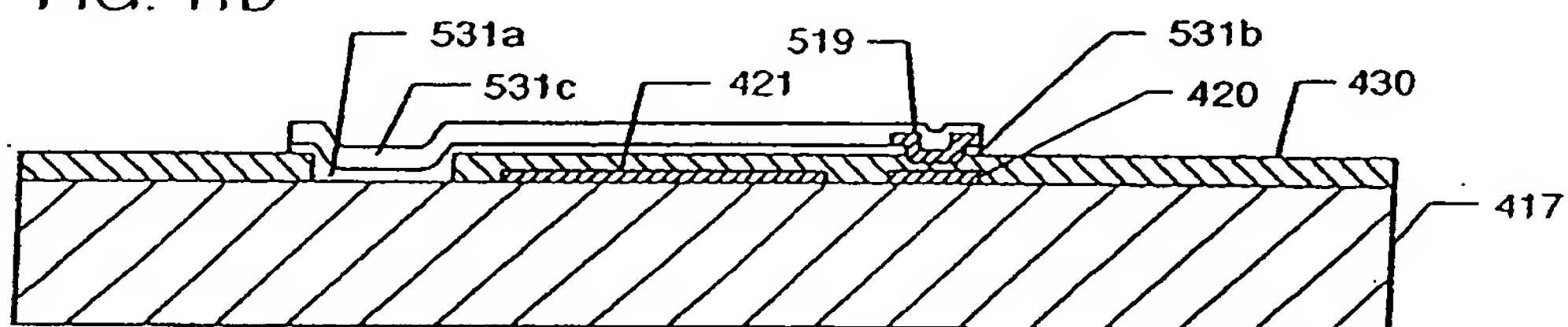


FIG. 11E

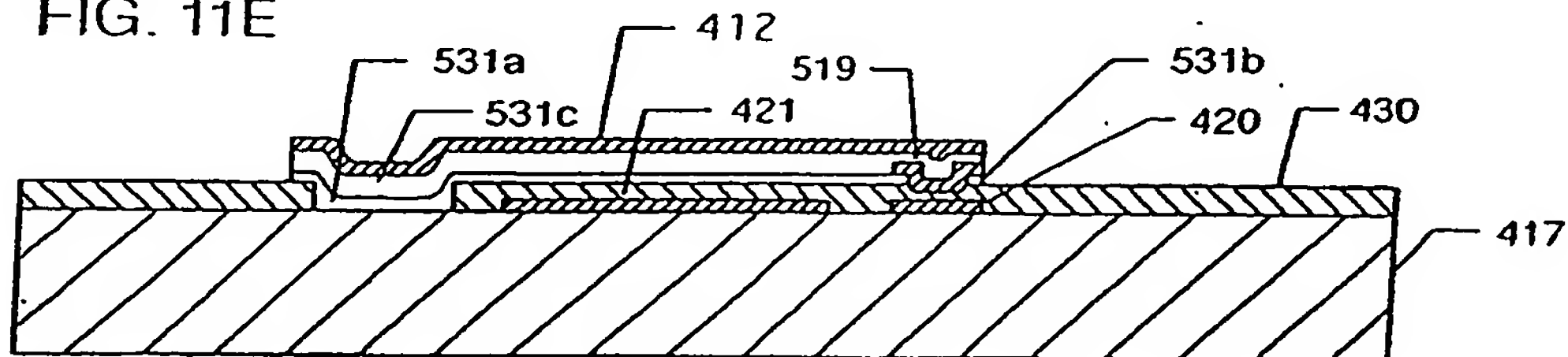


FIG. 11F

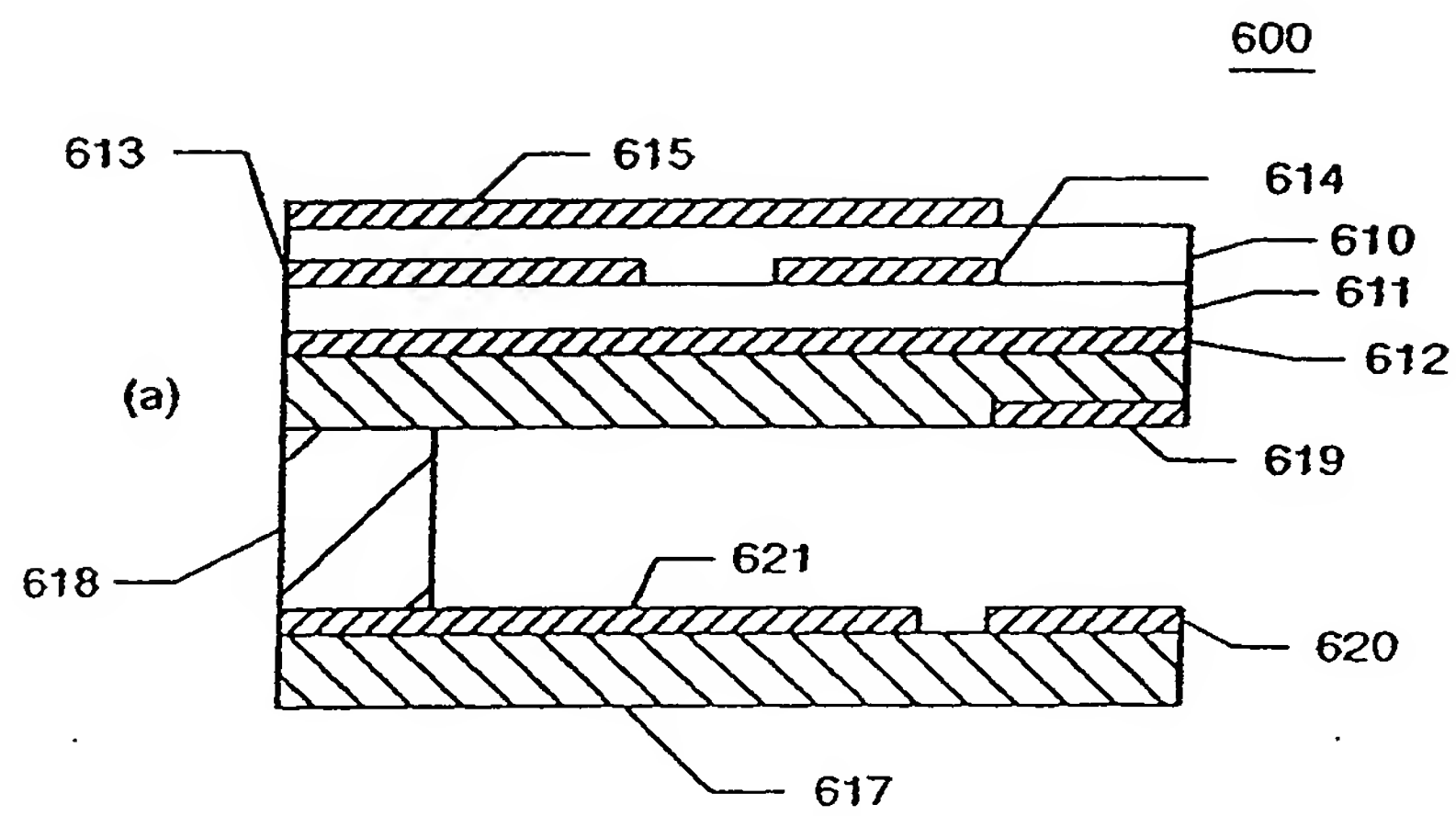


FIG. 12A

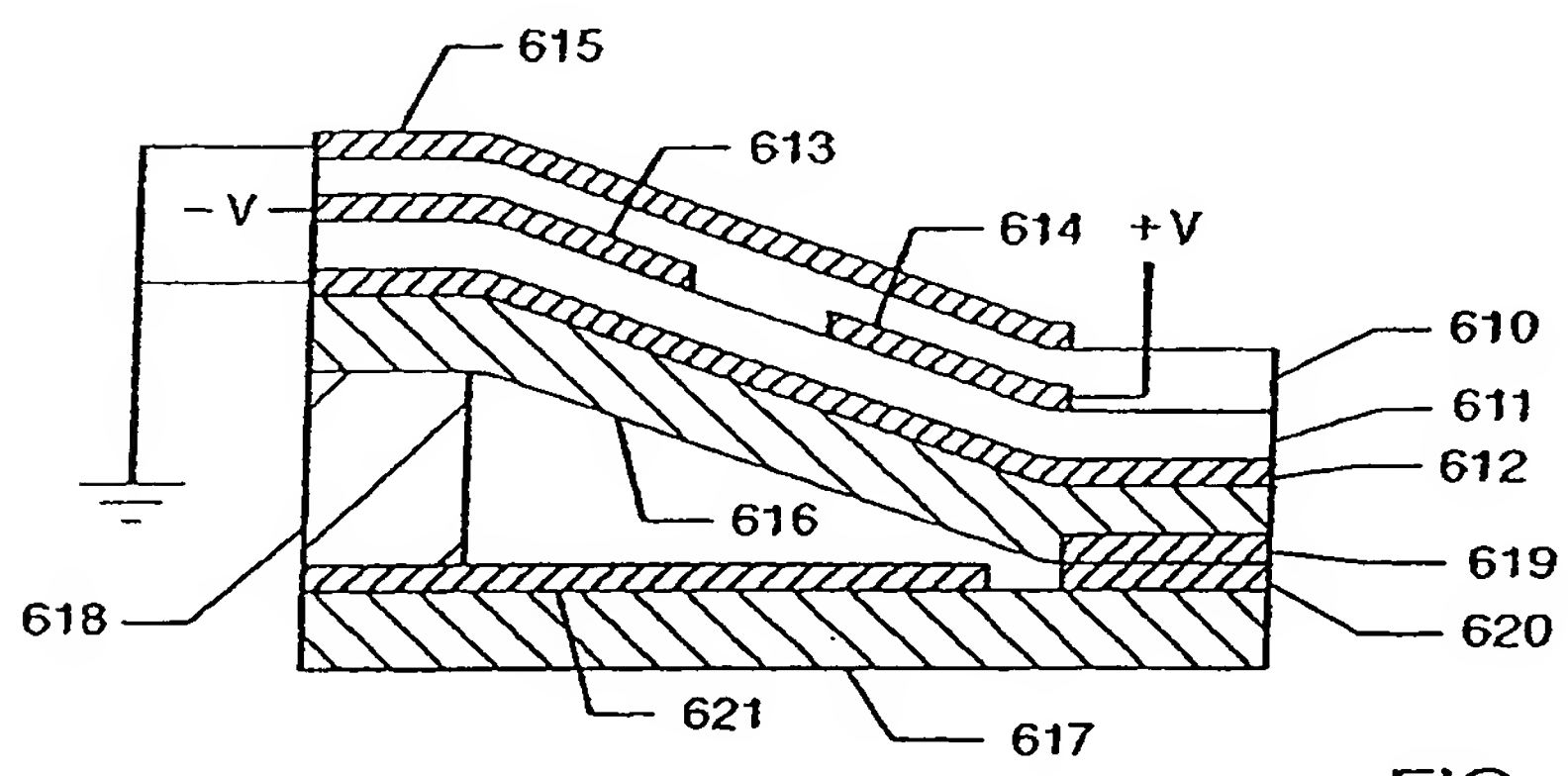


FIG. 12B